ELECTRICAL TRANSMISSION AND DISTRIBUTION

VOLUME VI

SUB-STATION WORK: PART II

VOLUME VI

ALTERNATING CURRENT SUB-STATIONS

BY

PHILIP KEMP, M.Sc.Tech., M.I.E.E., Assoc.A.I.E.E.

SUB-STATIONS

TESTING, MAINTENANCE AND OPERATION

BY

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AUTOMATIC SUB-STATIONS

BY

C. J. SARJEANT

ELECTRICAL TRANSMISSION AND DISTRIBUTION

A COMPLETE WORK BY PRACTICAL SPECIALISTS DESCRIBING MODERN PRACTICE IN THE TRANSMISSION AND DISTRIBUTION OF ELECTRICITY SUPPLY

EDITED BY

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CHARTERED ELECTRICAL ENGINEER

VOLUME VI

SUB-STATION WORK: PART II

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ELECTRICAL TRANSMISSION AND DISTRIBUTION

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PREFA

THIS book is one of great interest to all concerned in the running and maintenance of sub-stations. As these stations are frequently situated in districts remote from large towns, it is essential that attendants and maintenance engineers should be thoroughly conversant with the construction and working of the plant, so that they are able to rectify troubles without waiting for the arrival of expert assistance.

The first section of this volume deals with Alternating Current Sub-stations, which includes both rotary and static stations, while a few notes are given on Mercury Arc Rectifiers.

The second section also deals with both Rotary and Static Sub-stations, but in a rather more practical manner, while considerably greater detailed information is given on such points as The Testing of Switchgear, Overhead Line Tests, Care of Machines, Staff Organization, and Voltage Regulation.

It is only within comparatively recent times that it has become customary to run machines in isolated sub-stations without any attendant in charge. The reliability and efficiency of the automatic sub-station depend on the ability of the maintenance staff to keep in order the various items of circuit breakers, protective relays, and switches. The third section of this volume, dealing with Automatic Sub-stations, is full of valuable information to those concerned in this work. The author gives a clear description of the exact sequence of operations involved in the starting-up and shutting-down of the automatic plant. The working of a typical traction sub-station is also dealt with in detail, both with a single unit station and in the special case of multi-unit sub-stations.

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SECTION XX

ALTERNATING CURRENT SUB-STATIONS

(DESIGN AND LAYOUT)

FUNCTIONS OF SUB-STATIONS

THE sub-station provides the connecting link between the power station and the consumer. On the one side are the incoming lines, probably E.H.T., alternating current, and on the other side are the outgoing low-tension feeders which may be either direct current or alternating current. Many supply systems are now distributing alternating current to the consumers, in which case the sub-station has merely to provide for the change in pressure, but where direct current is supplied to the consumer, the sub-station not only has to effect a voltage change, but it has also to convert the electrical energy from the alternating current to the direct current form.

When the energy is supplied to the ultimate consumer in alternating current form, a transformer or static sub-station is all that is necessary, but when direct current is supplied a rotary sub-station is required, except where mercury arc rectifiers are employed.

For the purpose of stepping down (or stepping up) the voltage, transformers are invariably used in practice. (An exception to this is the transverter, which employs an E.H.T., direct current supply, converting the energy into alternating current at a lower voltage, or, alternatively, working on the opposite cycle of

operations, converting the alternating current to direct current at a very high voltage. The transverter, however, has not yet come into the field as a serious competitor of the rival methods.)

When conversion from alternating current to direct current is required there are several methods available. The first method, not now in much favour, is that of the motor-generator, which has given place largely to the rotary convertor and the motor convertor. A further rival is the mercury arc rectifier, which claims as an advantage the absence of moving parts, a claim not altogether justified, since a vacuum pump is necessary whenever steel containers are used, as they always are in the larger sizes.

Sub-stations are frequently called upon to fulfil a further function, that of interconnecting two separate supplies which may, or may not, come ultimately from the same power house. This interconnection necessitates the employment of boosting plant and the like, for the control of flow of power both in magnitude and direction.

TYPES OF SUB-STATION

A convenient method of classification thus consists of grouping them under two heads, (1) static substations and (2) rotary sub-stations.

The former group may be further subdivided into transformer stations and mercury arc rectifier stations, the former being employed when alternating current is supplied to the distributing network, and the latter when direct current is required. The two types of substation are thus not interchangeable.

The second group, that of rotary sub-stations, is much more elastic, as it is possible, though not desirable, to have motor-generators, rotary convertors, and motor convertors all present in the same sub-station,

since they all fulfil the same function. Moreover, where rotary convertors are employed, it is also necessary to have a transformer equipment for their operation, since rotary convertors work with a fixed voltage ratio between slip rings and commutator, and this necessitates the application of a low-tension alternating current supply to them. It is desirable, however, to limit the type of machine to one kind in any particular sub-station, since parallel running is much more likely to be satisfactory in such a case.

TRANSFORMER SUB-STATIONS

Practically all types of transformers are used at the present time for high-voltage sub-station work, and transformer sub-stations may be classified as

1. Outdoor sub-stations.
2. Indoor ,,
3. Underground ,,

Outdoor sub-stations may be further divided into overhead installations and surface installations, the former having the transformers mounted on poles or towers at points easy of access to the supply feeders, and the latter being arranged on the ground.

Indoor sub-stations are arranged in some kind of building which is intended to shield the equipment from the weather and to provide room where repairs and alterations may be carried out.

Underground sub-stations are installed under street pavements, in basements of buildings, on underground railways, in mines and such-like places. In these cases ventilation and drainage are of great importance.

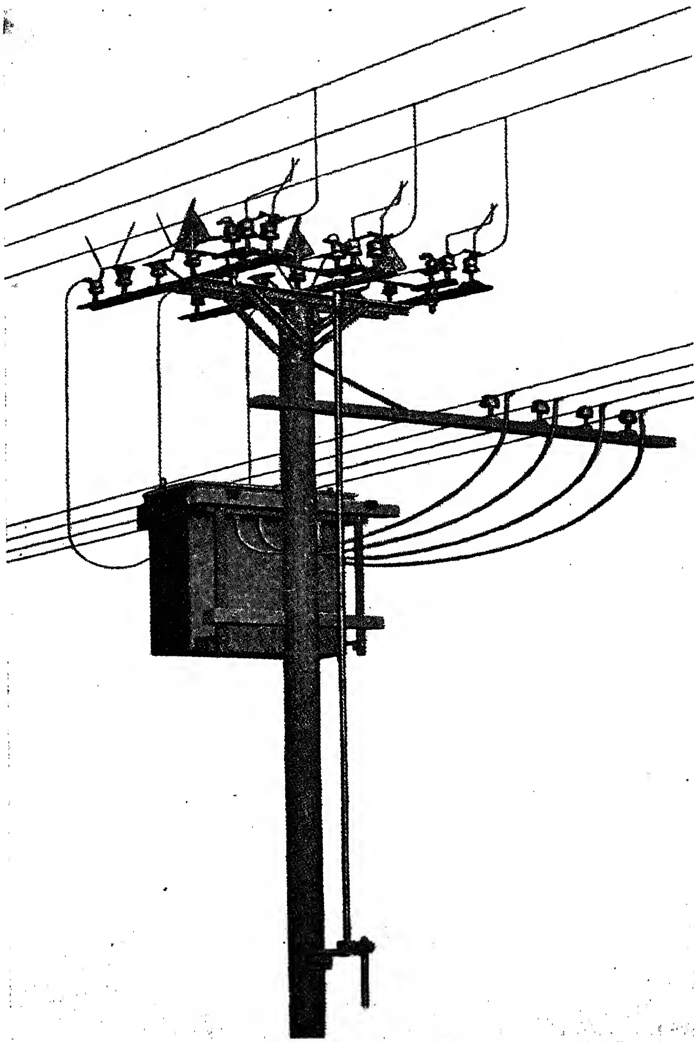
OUTDOOR INSTALLATIONS. OVERHEAD

Transformers mounted upon poles are now employed in capacities up to several hundred kVA, and wound for pressures up to 33,000 volts. The demand for

apparatus of this type has now reached such a stage that manufacturers have standardized their designs along definite lines. First and foremost, transformers for this class of work must be robust, both electrically and mechanically, and they must be waterproof and weatherproof. The question of electrical insulation and mechanical strength must be particularly looked into, since these transformers are often mounted in relatively inaccessible positions on outlying sites far removed from the power station or other sub-station, so that they are apt to be neglected in the matter of human attendance.

A more elaborate construction consists of a wooden or iron framework on which is erected a wooden platform. The transformers are mounted on this platform and are either wholly exposed to the weather or else are provided with some kind of protection.

The transformer windings should be impregnated in a vacuum, so as to prevent the coils from absorbing moisture, and, furthermore, the case should be made airtight. From this point of view, particular attention should be given to the joints between case and lid and the points where the insulating bushings enter the case. If these are not well fitted, snow and rain may be driven in by the action of the wind. There is a more insidious manner, however, in which moisture may penetrate the case, and this is by the breathing action of the transformer. As the windings and core heat up on account of the losses, the temperature rises and the heated air expands, some of it leaving the case at the various joints. Should a reduction of load occur, the temperature rise will diminish, the air will cool down to a certain extent and contract, thus drawing in a certain quantity of damp air from the outside. The moisture thus acquired ultimately settling on the windings produces a very harmful effect. On this account,



(*Metropolitan-Vickers*)

FIG. 1. POLE-MOUNTED TRANSFORMER WITH SWITCHGEAR EQUIPMENT

transformers for outdoor service are usually oil-immersed, although even here the moisture gets into the oil, adversely affecting its insulating properties.

Fig. 1 shows an example of a pole-mounted transformer with switchgear equipment. The overhead lines are tapped at suitable points and jumper connections are brought to the switching equipment, which is mounted on a special pole close to the transmission line. Any pull on the equipment due to line tension is thus avoided, and the air-break switchgear is removed from the immediate proximity of the lines. This switchgear usually includes an air-break horn gap switch, protective choke coils, horn gap lightning arresters and horn gap fuses. The switch is operated from the ground level by means of a handle which is fixed on the pole, this handle being attached to a suitable operating rod. It is usual to make provision for locking the handle in either the open or closed position to prevent interference by unauthorized persons. The low-tension side of the transformer is arranged for three-phase four-wire distribution.

OUTDOOR INSTALLATIONS. SURFACE

When larger powers have to be dealt with than can be effectively dealt with by transformers mounted overhead, it is the usual practice to arrange the plant on the ground level, and outdoor transformers have been installed on systems operating at as high as 150,000 volts. Sub-stations of this type are relatively simple and of low cost, whilst extensions are easily added at any time.

Attention has already been drawn to the necessity for making the tank as airtight as possible, and all exterior surfaces should be so arranged as to throw off rainwater quickly, water not being allowed to gather at any point on the tank. The terminals are now

arranged on top of the case instead of on the side, so as to simplify the wiring layout and the connection to the overhead lines. Mounting ladders and platforms should be avoided as far as possible, on account of the danger to human life in the event of a slip. On this account, temperature measurements are now usually effected by electrical temperature indicators which are mounted in such a position that they can be read from the ground.

The transformers themselves are mounted on a concrete foundation, and are usually of the oil-immersed self-cooled type, being provided with large radiator fins or, alternatively, with cooling pipes. Water-cooled transformers with their elaborate piping systems and cooling arrangements no longer find much favour.

The wiring and switchgear is generally carried on a steel superstructure.

Fig. 2 illustrates this type of outdoor sub-station, there being three 3000 kVA transformers stepping up the voltage from 6600 volts to 33,000 volts. Three-core cables are brought from the power station, terminating at isolating switches which are also connected to the transformer terminals. The whole of the switchgear is mounted in the open, this consisting of air-break switches, isolators, and hand-operated automatic oil circuit breakers. The latter are also mounted on concrete foundations, one being shown in the foreground in the illustration.

INDOOR TRANSFORMER SUB-STATIONS

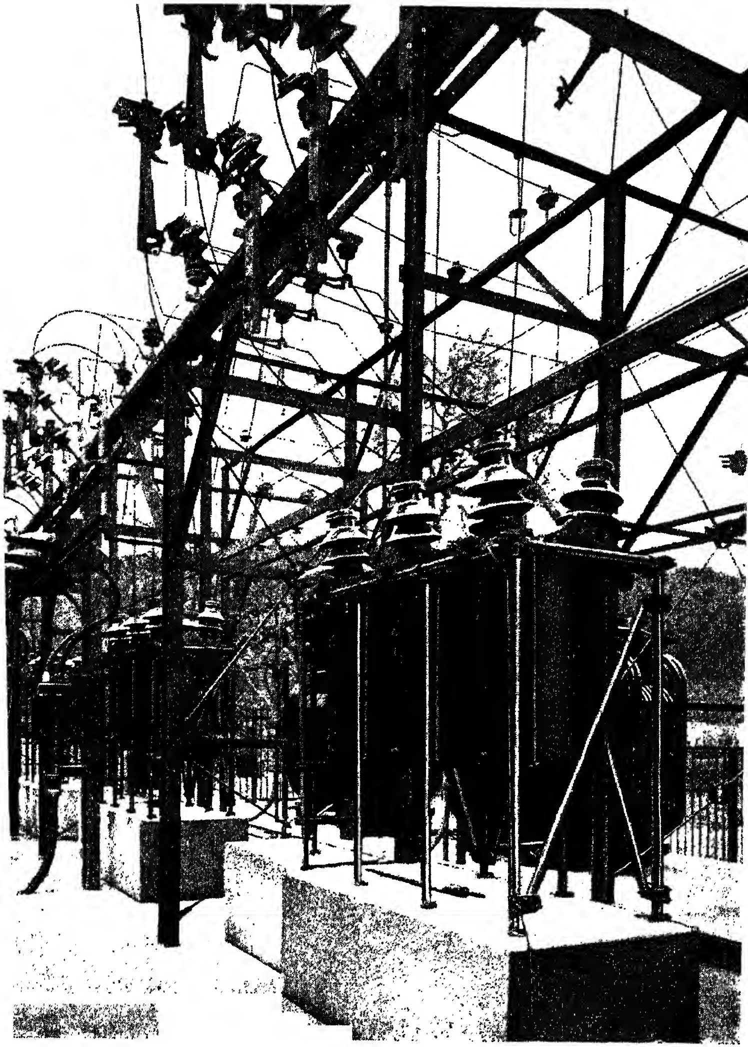
These may be conveniently subdivided into two types, namely, those containing artificially cooled transformers and those in which the plant is cooled by natural radiation. For the former type to be justified, the interest on the saving in capital expenditure must exceed the annual cost of attendance. Increased

output at any particular sub-station is obtained by adding similar units (not necessarily of the same kVA capacity), these being connected in parallel with the existing transformer groups.

In designing a sub-station, the following three guiding principles should be borne in mind : (1) The apparatus must be properly designed on sound lines ; (2) arrangements must be made for the isolation of faulty apparatus by the employment of automatic devices, and (3) a sufficient reserve of plant should be maintained in readiness to meet abnormal circumstances. The first two considerations do not affect the general size and design of the building, but the third necessitates the allocation of extra space, and materially increases the size of the building required.

The provision of reserve plant also involves the division of the equipment into similar groups, the output of which must be so proportioned that, in the event of the failure of one group or section, the remainder of the plant will have sufficient capacity to maintain the load. In making provision for abnormal circumstances of a temporary character, the overload capacity of the various groups may be taken into account, since otherwise a greater amount of spare plant must be kept available. Where a group of sub-stations of similar type is to be considered, each spare may, of course, be made to serve for a number of sub-stations.

The building itself should be of fireproof construction, and should be of such a size that the equipment is not cramped for space. Room should also be provided for the carrying out of any necessary repairs. The installation, maintenance, and repair can then be carried out at the minimum cost and maximum convenience. In one type of transformer house the apparatus and wiring is installed in the open, but in another type it is installed in individual compartments. The



(*Metropolitan-Vickers*)

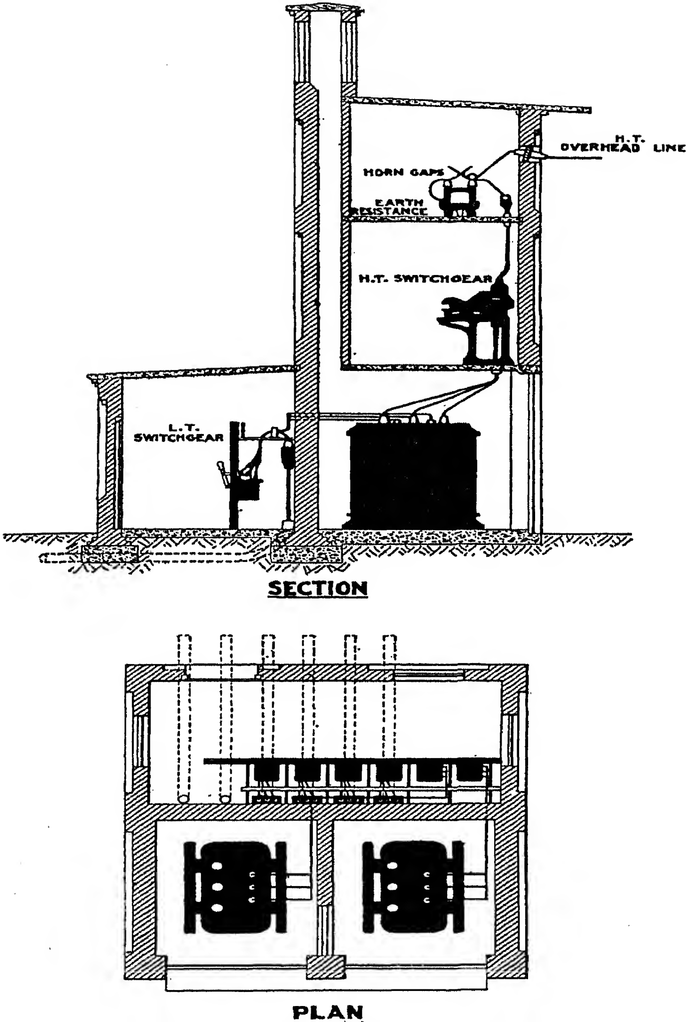
FIG. 2. OUTDOOR SUB-STATION

transformers themselves are frequently housed in separate fireproof compartments, so constructed as to isolate any burning oil in the event of trouble.

Sub-stations of this type are rarely heated by special means, and when any fall of temperature occurs, water is apt to condense. If the transformer tanks are not watertight this forms a possible source of trouble, and the addition of properly constructed breathers is an advantage.

An example of a small indoor transformer sub-station is shown in Fig. 3. The incoming high-tension overhead line is brought in through a wall insulator and is connected to one horn of a horn gap lightning arrester before going away to the high-tension switch-gear. The other side of the horn arrester is connected to earth through a resistance. The whole of this gear is kept on the second floor, the first floor being devoted to switchgear. The high-tension cables drop straight away from the switchgear, through the floor, on to the transformers, on the ground floor. The low-tension cables are taken away, through the wall, to the low-tension switchboard which is in a separate compartment. After passing through the low-tension oil switch, the cables are taken straight away to their underground run. The plan view shows that the two transformers are housed in separate compartments, whilst the elevation shows the flue which is provided for the purposes of ventilation.

In Fig. 4 is shown a rather more elaborate arrangement for operating on 20,000 volts–6000 volts. Both sets of lines are here brought in by underground cables which are taken to the respective busbars arranged above the switchgear on the first floor. No chimney is provided, but ventilation under the roof and an air duct inlet on the ground level provide efficient ventilation. At one end is an entrance and repair well for the



(*I.E.E. Journal*)

FIG. 3. ARRANGEMENT OF OVERHEAD LINE SUB-STATION

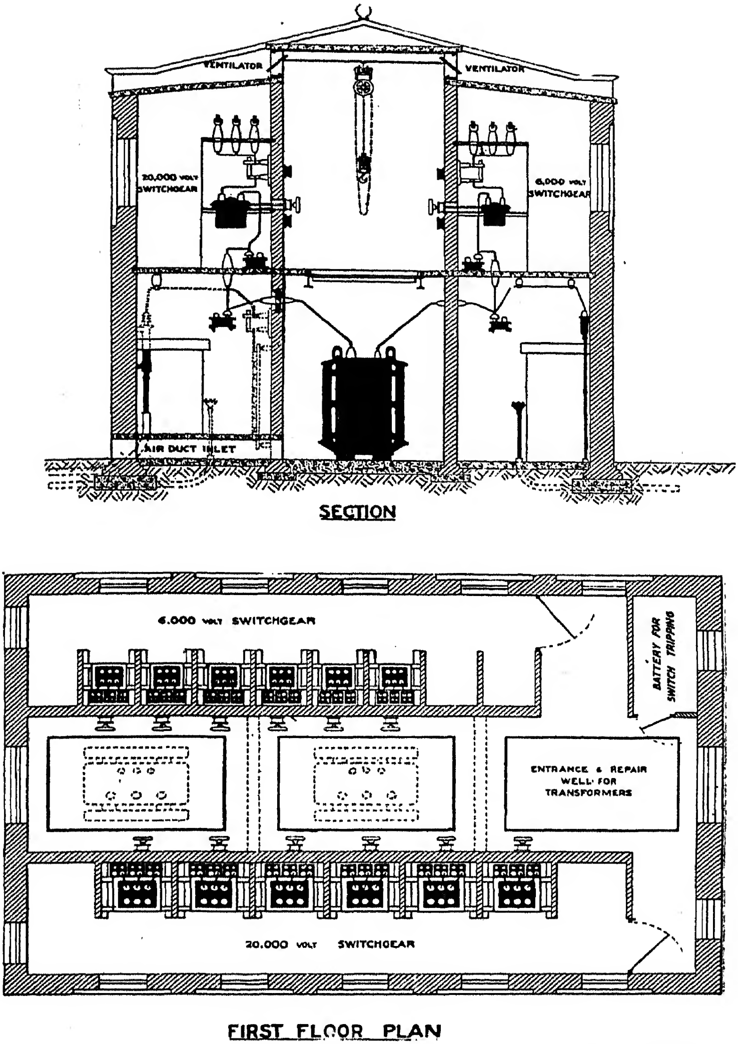
transformers, the movement of which is effected by the aid of an overhead travelling lifting tackle. A small room is also provided in one corner for a battery employed for switch tripping.

UNDERGROUND TRANSFORMER SUB-STATIONS

In installations of this type it is the usual practice to install ordinary oil-immersed self-cooled transformers. In urban districts it is fairly common practice to set up transformer installations in basements and in manholes under the pavements. In the latter case, particularly, the tanks should be rendered watertight and airtight, and should be provided with an extra amount of radiating surface. In some designs the tank lid is provided with a vent which is covered by a thin airtight metal diaphragm, so that if the air pressure inside the case becomes excessive, the diaphragm will rupture. All the insulating bushings should be made damp-proof, but the transformer should be easy of access and easily disconnected, often a somewhat difficult matter, since space is usually restricted.

VENTILATION

The necessity for ventilation with transformers of a moderately large output is a serious consideration. Transformers are usually designed on the assumption that the maximum temperature coincides with an unlimited supply of air, and this condition is never attainable in a sub-station, as the cost of the building would be prohibitive. A ventilating louvre is cheaply constructed, but a much better draught is obtained by means of a flue, air being admitted somewhere at the bottom of the transformer chamber. The size of this flue should be calculated on the basis of the losses of the largest size of transformer that the house will be required to accommodate. The flue should not be built



(*I.E.E. Journal*)

FIG. 4. TRANSFORMER SUB-STATION 20,000–6000 volts

of sheet iron or similar material unless precautions are taken to prevent the loss of draught through radiation.

RESERVE PLANT

The consideration of the reserve plant is of vital necessity when settling the number and size of the various transformer banks in a sub-station. As an example, consider the case of a sub-station which is to be called upon to deal with a load of 1000 kVA, with one section in reserve, three-phase transformers being adopted. With the minimum number of two transformers (one as reserve), these would each have to be of 1000 kVA capacity, giving a total plant capacity of 2000 kVA. With three transformers (again one in reserve), these would be each of 500 kVA capacity, giving a total plant capacity of 1500 kVA, a cheaper arrangement since three 500 kVA transformers cost less than two 1000 kVA transformers. With four transformers the total plant capacity is reduced to 1333 kVA, and it would appear at first sight as if the larger the number of transformers, the more economical is the arrangement. This is not so, however, as the cost per kVA rises when the size of the transformer falls, and there comes a limiting size beyond which an increase in the number of units installed actually leads to an increase in the total cost, in spite of the fact that the total plant capacity is less. For example, two 100 kVA transformers are cheaper than three 50 kVA ones, although the total capacity is 200 kVA as against 150 kVA. Obviously, the best size of unit, considered from this point of view, depends upon the manufacturer's costs and these probably vary from year to year. Then there is also the cost of the switchgear to be taken into account. A further point against the employment of a multiplicity of small units is that the efficiency is not so high in the smaller sizes and the

additional losses represent an extra annual charge. The balance of advantage and disadvantage is thus seen to be in favour of the smaller number of units, but as the size increases there comes a point when the reverse is the case.

THREE-PHASE *v.* SINGLE-PHASE TRANSFORMERS

It was explained above that the smaller the kVA capacity of the transformer, the greater is the cost per kVA, so that it will be quite understood that one 750 kVA three-phase transformer is cheaper than three 250 kVA single-phase transformers, but on the other hand, the latter arrangement only requires a reserve capacity of 250 kVA as against 750 kVA in the three-phase case, since it is assumed that only one phase will fail at once. Actually, this reasoning is not altogether sound, since it is found in practice that when one phase goes down, another phase is quite likely to follow suit, owing to the abnormal conditions which are set up momentarily. For this reason, it is a safer policy to provide two single-phase spares, but even then the single-phase scheme has the advantage on price, since five 250 kVA single-phase transformers have to be considered against two 750 kVA transformers in the example chosen. If the size were reduced, however, the advantage would quickly come on the other side. In any case, the three-phase unit has the advantage on the score of the reduced floor space required. The above comparison is not quite fair to the three-phase unit since, in a densely loaded urban area, spares may be kept at some central site ready for use in a number of positions, but this consideration obviously does not apply to cases where plant has to be installed in readiness to take up load at a few moments' notice.

When dealing with very large sizes of units, the

question of transport is frequently a deciding factor, the headroom of bridges and of railway tunnels between the manufacturer's works and the site imposing limiting values to the dimensions.

VARIOUS CONNECTIONS OF THREE-PHASE BANKS

There are many ways in which three-phase transformers, or three single-phase transformers, can be connected. The most common arrangement is the star and the delta, either of which may be on primary or secondary. Transformers with one type of connection may or may not be capable of operating in parallel with transformers connected according to a different scheme. On a particular system, standardization in this respect is, of course, of great importance.

Various systems will be briefly considered. In the star-star connection, the cross section of the conductors is a maximum, the total number of turns and the total quantity of coil insulation is a minimum, resulting in a high copper space factor and mechanically robust windings, an important point when considering possible short-circuit conditions. The neutral point is available on both sides for earthing purposes, and unbalanced four-wire supplies can then be obtained without interfering seriously with potential conditions. On the other hand, the neutral potential is unstable unless it is solidly earthed and trouble due to harmonic magnetizing currents may be encountered. The addition of a tertiary delta winding obviates this disadvantage, but the extra cost is a factor.

With the delta-delta connection, closed circulating paths are provided for any third-harmonic magnetizing current, but no neutral point is available for earthing purposes. Large unbalanced loads can be dealt with, the potential conditions being not greatly upset, in

fact, a failure on one leg of the delta will not put the bank out of action, the remaining two legs maintaining a true three-phase supply. It has the disadvantage that the amount of copper and of coil insulation is greater than in the star-star case and that a four-wire supply cannot be given without the aid of additional auxiliary apparatus.

The star-delta connection has the advantage that the primary neutral may be earthed and that oscillation of the primary neutral potential at third harmonic frequency is eliminated, since there is a closed path in the secondary for the circulation of third harmonic magnetizing currents. The connection suffers from the disadvantages that there is no secondary neutral point for earthing in the case of a step-down transformer and that the secondary winding is apt to be weaker than with other types of connection in the case of a step-up transformer, the reason being the greater number of turns that is rendered necessary.

Probably the most common arrangement is that of the delta-star. Third harmonic pressures are eliminated as in the previous case, giving rise to a stable neutral potential, whilst the secondary neutral may be earthed or it may be utilized for the purpose of giving a four-wire supply. Even if this latter be unbalanced there is practically no voltage effect. There is no primary neutral point for earthing, but this is not a serious disadvantage, since the primary side is usually earthed at the generating station.

TEE AND SCOTT CONNECTED GROUPS

Tee-tee connected groups are not greatly used in this country, but they have certain advantages of their own, one of which is that they may be employed for supplying a load which may ultimately grow, when a third single-phase transformer may be added and the

group changed over to the delta-delta connection. When this is contemplated, the two original transformers must be made interchangeable. In this case, the total rated kVA of the group must be $15\frac{1}{2}$ per cent greater than the actual load supplied, which offsets any saving obtained in other directions.

The Scott connection is used for effecting a three to two-phase transformation or vice versa and has had one particular application of late years. In certain cases where both a direct current and an alternating current supply is available, a change-over of a particular portion of the load may be considered desirable. Large individual consumers may have their own local sub-station, and their own circuit wiring may have been originally intended for a direct current three-wire supply. The same wiring could be employed with the aid of a two-phase three-wire supply, this being obtained from the three-phase E.H.T. supply by means of a group of Scott connected transformers.

EARTHING

Experience has shown that earthing the neutral results in greater freedom from breakdown than when it is left insulated, particularly in the higher voltages used on transmission systems. With the lower voltages there is also the question of danger to life, for if the low-tension system is earthed, the maximum voltage to earth is, of course, equal to $\frac{1}{\sqrt{3}}$ times the line voltage, but if the neutral be left insulated, the actual potential to earth may greatly exceed this figure. On the E.H.T. side this consideration is naturally of no moment, since the effects of a shock are liable to be fatal in either case.

With an insulated neutral, an earth fault does not

make itself immediately apparent, but if the neutral is earthed, a fault on the system at any other point constitutes a short-circuit on some portion of the windings, thus bringing into action the automatic protective devices and cutting out the faulty section.

On an insulated system, the voltage to earth of any line conductor may reach any value up to the break-down voltage of the insulators to earth, even although the normal voltage between lines be maintained. Such a condition may be set up by static charges on overhead lines caused by rain, sleet, snow, wind, etc. If the system is earthed, these may leak away as they appear, but if the line is insulated, other methods must be employed for dealing with them.

Earthing should be carried out at one point only on a system. If multiple earths are adopted there may be a continual flow of harmonic currents through the earth, and these might give rise to telephone interference.

A system may be earthed solidly or it may be earthed through a resistance or reactance coil. A common device consists of an air-cooled resistance in the form of a cast grid. The Brazil resistance is another form of earthing resistance. The actual ohmic value depends upon the highest relay setting, and it is often designed to carry for a quarter or half a minute a fault current up to twice the largest current necessary for operating the most insensitive relay.

When it is desired to earth a delta-connected group, auxiliary apparatus must be included for this purpose. This usually takes the form of a three-phase choking coil with interconnected (or zig-zag) windings. The neutral point of this is earthed, either directly or through a resistance. Alternatively, three resistances may be employed on the line sides of the choking coils.

BALANCING

It is, of course, very desirable that the loads on the three phases should be balanced, but where this is impossible, as, for example, when a three-phase four-wire supply is being given, attempts should be made to rid the E.H.T. side from the effects of the lack of balance as far as possible. Sometimes it may be desirable to instal transformers with interconnected (or zig-zag) windings, as is done in the case of static balancers, but this results in an increase in the price and a possible decrease in efficiency, so that this remedy is not sought unless the trouble is very pronounced.

PARALLEL OPERATION

With three-phase banks the first essential consideration for parallel operation is that the phase rotation of the various groups must be the same, that is, the voltages must attain their maximum values in the proper sequence. Once this is determined and the wiring fixed, there is no need to trouble about it any further. Transformers, however, which operate in parallel satisfactorily on no-load are not necessarily satisfactory on load, for they may not share the load equally or in proportion to their rated outputs. The extent to which a transformer picks up load when operating in parallel with others depends upon its percentage impedance pressure drop. If this figure is high, then that particular transformer will not take its fair share of the load. Again, a given percentage impedance pressure drop may have a larger proportion due to resistance in one case than in another, with the result that although the kVA loads on the two banks of transformers may be equal, yet their kW outputs may be different, owing to their operating on different power factors. From this it is obvious that for satisfactory

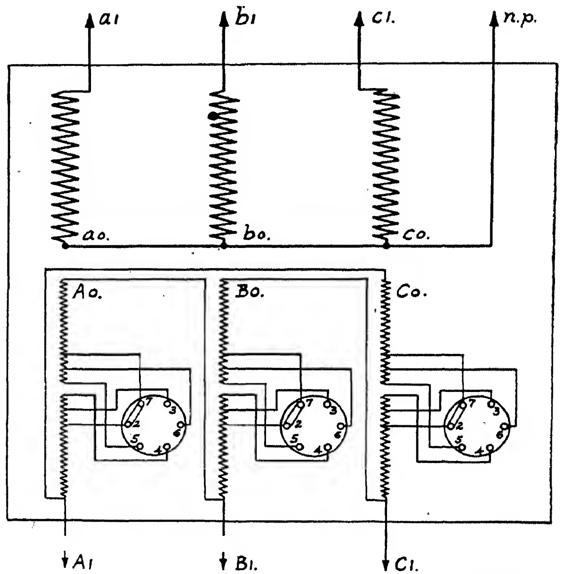
parallel operation, not only should the percentage impedance pressure drops be equal, but the percentage resistance pressure drops as well. The phase angle between primary and secondary terminal voltages should also be the same.

TAPPINGS

Tappings for altering the value of the voltage by a slight amount may be divided into two types—(1) where the transformer has to be made dead in order to effect the change and (2) where the change is made whilst the transformer is still in circuit. Connecting the tappings in the high-voltage winding has the advantage that the current dealt with is a minimum, and this is usually done. They are generally brought out from the middle point of each leg. In this way, the overall length of the windings is unaffected by changing the tapping points, and the more heavily insulated end coils always remain connected to the supply terminals. Fig. 5 shows a typical diagram of connections of a three-phase delta-star connected transformer showing the tappings. The maximum voltage at the secondary terminals corresponds to the minimum number of turns on the primary winding, and this is obtained with the tappings 2–7 connected together. Minimum secondary voltage is obtained from the tappings 4–5. Corresponding tappings in all three legs should, of course, be used in combination. These tappings are under oil, above the main transformer core.

For regulating the voltage whilst the transformer is in circuit, contactor type step switches may be employed. The first contactor puts the complete winding in circuit, one line being connected to the middle point of a small choking coil the outer ends of which are short-circuited and connected through the contactor to the winding. The two halves of the choking coil thus

act in opposition, rendering it practically non-inductive. The next step removes the short-circuit across the choking coil, the transformer winding now being connected to one end only. The next contactor connects the next tapping point to the other end of the choking



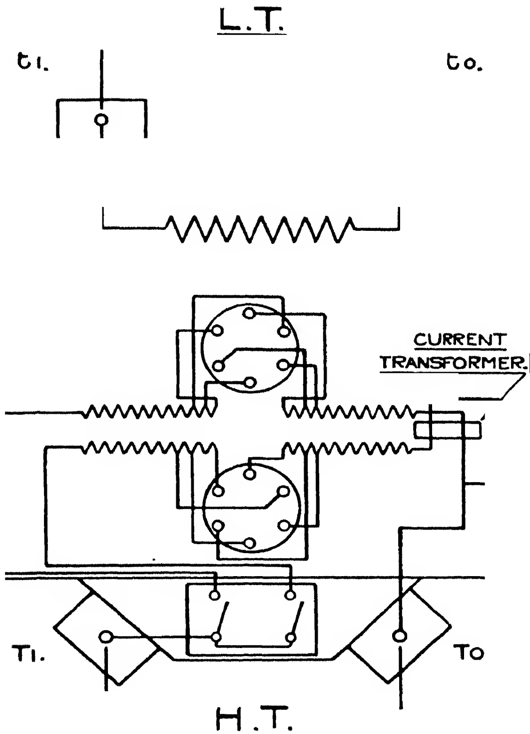
(*Ferranti*)

FIG. 5. DELTA-STAR CONNECTED TRANSFORMER WITH TAPPINGS

coil, which is now connected directly across one section of the transformer winding. The original transformer tapping is now disconnected and the two ends of the choking coil short-circuited as before. The transformer is now on load on the second tapping and this series of operations is repeated for each other tapping.

An alternative method requires the tapped winding

to be split into two parallel halves, one of which carries the full load whilst the tappings on the other are being altered. These parallel windings normally share the



(*Ferranti*)

FIG. 6. TRANSFORMER TAP CHANGING ON LOAD

load equally, and must have sufficient inherent reactance to limit the circulating current during the change-over period. A typical example of this arrangement is shown in Fig. 6. The parallel windings are arranged

as two cylinders on the core, relatively displaced by a small amount in an axial direction so as to give the necessary reactance to limit the circulating current. This displacement is, however, quite small in practice. When it is desired to change the voltage, one of the windings is open-circuited, and the tappings on this winding changed. During this short interval of time, the other winding carries the total current. The disconnected winding is now reconnected and the other one open-circuited. During the short time that both halves are connected in parallel on different tappings, a circulating current flows, but this is limited in magnitude by the reactance between the two halves as mentioned above. The tappings on the second half are now altered to suit the first one, and, finally, it is reconnected when the operation is complete.

PROTECTION

The protection of the transformers and the feeders from the effects of short-circuits and other faults is an important question, and protective devices of some kind or another are always included.

As a protection against short-circuit stresses, transformers should always possess a certain minimum inherent reactance. In addition, various systems of protective gear are employed, those in most general use being (1) core balancing system, (2) Merz-Price circulating current system, (3) Merz-Beard self-balancing system, and (4) McColl circulating current system. Feeder protection is also often provided by the Merz-Hunter split conductor system.

ROTARY SUB-STATIONS

Where a low-tension direct current network has to be supplied from an E.H.T., alternating current system, some form of converting apparatus has to be provided.

Of the various methods for converting electrical energy from the alternating current to the direct current form, only three need be considered in a modern sub-station, these being (1) the rotary convertor, (2) the motor convertor, and (3) the mercury arc rectifier. Of these, the most commonly met with at the present time is the rotary convertor, but the other two form serious rivals to it and its permanent supremacy is by no means assured.

Rotary sub-stations are, naturally, more elaborate than those employing static apparatus, and are always of the indoor type, it not being practicable to install rotating machinery in the open air.

In the case of rotary convertor installations, in addition to the rotating machines, there must be a transformer equipment as well, since the rotary convertor only works, within narrow limits, with a fixed voltage ratio between slip rings and commutator. This ratio is different for different numbers of phases, but it is always of such a value as to preclude the possibility of applying the E.H.T. alternating current supply directly to the slip rings. In addition, there is, of course, the switchgear, both for E.H.T. (and low-tension possibly) on the alternating current side, and low-tension on the direct current side. In many cases a secondary battery may also be present.

The great point to consider in laying out a rotary sub-station is the question of how to get the maximum amount of plant installed for a minimum amount of floor space. A second important point consists in disposing the plant in such a manner as to reduce the cabling to a minimum. For this purpose, the transformers feeding a rotary convertor should be as close to it as possible, so that the low-tension leads from the transformer secondary terminals to the slip rings may be short. Frequently, these are directly connected

without any intervening switchgear, but where tap-starting or pony motor starting is employed, low-tension alternating current switchgear will be necessary. Sometimes, an attempt to save floor space is made by placing the transformers in a basement or on a gallery, but this practice cannot be recommended on account of the greatly increased lengths of cable runs which it involves.

The incoming E.H.T. power may be conveniently controlled by means of a cubicle type of board, which is safe, economical in space, and neat in appearance. Ironclad cubicles are used as well as those of stone and brickwork. The low-tension switchboards, both direct current and alternating current, are largely standardized and call for no special comment.

The exact position of the cable troughs, tubes, and ducts is very important. The E.H.T. cables from the switchboard to the transformers are generally run in stoneware ducts, the cables being either lead-sheathed, paper-insulated, or rubber covered. Tightly fitting wooden bushes should be used to close the entrance to the ducts, so as to keep out rats and mice.

The connections between transformer and slip rings may consist of lead-sheathed paper-insulated cable where the current is not very large, but for very heavy currents it is preferable to run the connections on porcelain insulators in shallow ducts which may be either covered in permanently or by removable iron plates. The conductors in these ducts will consist of bare copper strip, connected at the ends to lengths of cable running to the transformer and slip rings respectively.

On the direct current side also, bare copper strip on porcelain insulators may be run in ducts from the commutator to the switchboard. The alternative is stoneware ducts and insulated cable.

The cables leading to the feeders outside the sub-station should be laid in ducts leading out of the trench behind the low-tension switchboard. Inside the cable trench itself, the cables should be arranged on racks in an orderly manner, using porcelain insulators and allowing ample clearance.

Light meter wiring is usually carried in iron tubes or else on porcelain cleats.

A last item in the equipment of a sub-station is an overhead travelling crane which is obviously very desirable, whilst another auxiliary in the form of a compressed air plant is of immense value for cleaning purposes.

LAYOUT OF ROTARY CONVERTOR SUB-STATIONS

The first point is that of floor space. The area desired and the space available are often quite different, particularly when the sub-station is situated in a dense industrial area with a rapidly increasing power demand.

The rotary convertors themselves should be arranged wherever possible, with their axes of rotation parallel to one another. A very suitable position for the E.H.T. and low-tension switchboards respectively is then found on opposite sides of the rotary convertors with their lengths parallel to each other and at right angles to the axes of rotation. The commutator ends of the convertors would face the direct current switchboard on one side and the slip ring ends would face the E.H.T. switchgear on the other. If the full width of the sub-station is occupied by this arrangement, the transformers could conveniently be placed at one end of the building. An alternative arrangement to this is to mount the E.H.T. switchgear on a gallery underneath which are placed the transformers, each opposite to its own rotary convertor. This method of arrangement

leads to a reduction in cable costs, but is more expensive on account of the gallery. With such a layout, sufficient space must be left for the transformers to be moved forward in order that they may come within reach of the crane, to enable them to be lifted out of their tanks for inspection or repairs. The transformer tanks must

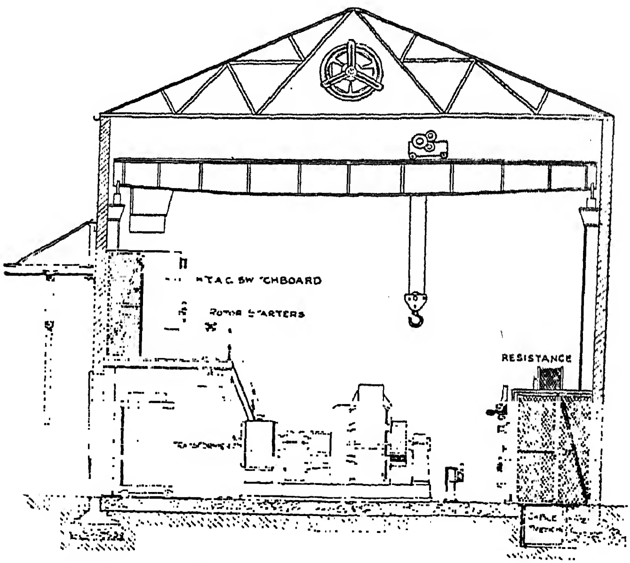


Fig. 7a. G.E.C. Rotary Convertor Sub-station
End elevation

be mounted on wheels or rollers, which should run on rails provided for the purpose. Where space is restricted, three-phase transformers are preferable to three single-phase transformers, since they occupy less room.

A typical example of a rotary convertor sub-station is shown in Fig. 7. Three rotary convertors, each

designed for pony motor starting, are laid down in a row, their respective transformers standing opposite to them under a gallery on which is erected the E.H.T. switchboard. In this particular case, in order to save the

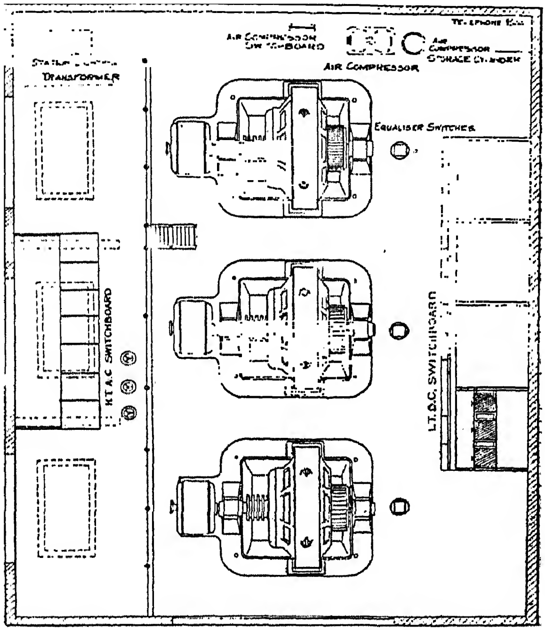


FIG. 7B. G.E.C. ROTARY CONVERTOR SUB-STATION
Plan view, showing placing of machines

space required for drawing out the transformers, arrangements are made to take them out at the side of the building where suitable tackles are provided for lifting purposes. The convertors are started from the gallery by means of pedestal type starters, the auxiliary apparatus being mounted on the under side of the gallery. The low-tension alternating current cable runs

are thus kept down to a minimum. The direct current switchboard is on the other side of the sub-station and immediately over the cable trench which takes the outgoing feeders. For lighting purposes a special transformer is provided, whilst an air-compressor set is installed for cleaning and general maintenance.

SIX-PHASE ROTARY CONVERTORS

It is the standard practice at the present time to design rotary convertors for six-phase working on three-phase systems, except for small outputs where three-phase machines are employed. The reason for this is that the six-phase machine possesses various advantages over its three-phase counterpart, and the provision of the six phases is easily effected by suitably connecting the various transformer secondaries. The advantages which are gained are that, owing to the more complete neutralization of the direct and alternating currents in the armature winding, the size of the six-phase machine is slightly less. The armature heating also is more uniform. On the other hand, the six slip rings are more costly and occupy more space than the three, and there are also the additional leads from the transformer secondaries to be provided.

TRANSFORMER CONNECTIONS

There are various methods of effecting the phase duplication, but the one most commonly adopted consists in bringing out all six ends from the secondary windings, and, instead of connecting three together, to form a star point, leaving them without any direct connection to each other. The two ends from the first secondary are connected to the slip rings corresponding to phases 1 and 4, these having a phase difference of 180°. The second secondary is 120° out of phase with

the first, so that the front end must be connected to slip ring No. 3, which is 120° out of phase with slip ring No. 1, there being a phase difference of 60° between adjacent rings. The rear end of this secondary goes to slip ring No. 6. The third secondary has its front end connected to slip ring No. 5 and its rear end to slip ring No. 2. If it is desired to earth any or all of these secondaries, mid-point tappings should be brought out from the windings. These tappings are also necessary when the direct current side is operated on the three-wire system.

METHODS OF STARTING

Rotary convertors may be designed for starting from either the direct current or the alternating current side.

When the set is started from the direct current side, it is run up to speed as an ordinary shunt motor, and similar starting gear may be used. In many cases, however, it is possible to use a simpler form of starting switch than is generally adopted with direct current motors, since the no-volt and overload releases may not be required if the necessary protection is provided on the direct current switchboard. In such cases, the starting switch often takes the form of a single-pole knife switch having five or six contacts, the resistance being placed in some suitable position behind the switchboard.

The set must be synchronized when the correct speed is attained, and this may be done on either the high-tension or the low-tension side of the transformers. It is preferable to carry out this synchronizing on the high-tension side, particularly in the case of the larger machines, since the currents dealt with are smaller. If performed on the low-tension side, the heavy knife switches which would be required would be difficult to operate with sufficient rapidity. The necessary speed

regulation for synchronizing is obtained through the shunt field regulator of the rotary convertor.

When starting from the alternating current side there is a choice of two main methods—(1) by means of tappings on the transformers and (2) by means of a pony motor.

Tap-started rotary convertors must be provided with a complete damping winding which will act as a squirrel cage during the starting period. The set is then run up to speed as an induction motor by applying a voltage of about one-quarter or one-third of the full pressure to the slip rings, this reduced voltage being obtained from the tappings on the transformers. When running up to speed the direct current field circuit must be open-circuited on account of the dangerous voltages induced in it. In some cases it is split up into sections by a field-splitting switch. Since the machine runs up as an induction motor it will only run to within about 1 per cent of synchronous speed. There must always be a certain amount of slip as long as it is working on the induction motor principle. The direct current field circuit is now closed through a resistance, and an increased voltage applied to the slip rings. This direct current field current produces definite poles on the field system, whilst another set of poles is produced on the armature by the action of the alternating currents flowing in it. The field due to the latter rotates at synchronous speed with respect to the armature conductors themselves, but in the opposite direction to the actual speed. This field is, therefore, actually rotating at slip speed, so that when this is sufficiently low, and the direct current field current sufficiently strong, the two sets of poles lock magnetically with one another, or, in other words, the set pulls itself into synchronism. When started in this manner it is possible for the voltage to appear on the commutator with reversed polarity, and on this

account a field reversing switch is supplied. When this is thrown over, the field is first demagnetized so that the armature drops out of synchronism. When the armature has slipped back through a pole pitch, the voltage will build up with the right polarity if the field circuit is re-made in the original direction.

The pony motor method of starting consists of employing a separate induction motor, and may or may not require separate synchronizing depending upon the arrangement adopted. In the former case, the induction motor is usually provided with two less poles than the main convertor, so that synchronous speed may be attained. Synchronizing is then carried out in the usual manner. In the self-synchronizing arrangement, the induction motor stator windings are connected in series (and not in parallel as in the former case) with the convertor armature at starting. The induction motor starts the convertor, the latter having its field winding open-circuited at the commencement. The greater proportion of the applied voltage is now across the starting motor. When synchronous speed is attained and field is applied to the convertor, the starting motor acts as a synchronizing reactance and permits the convertor to synchronize itself automatically. The induction motor stator windings are now short-circuited and the convertor is ready for paralleling on to the direct current busbars.

VOLTAGE REGULATION

If no account were taken of the inherent voltage drops in transformer and rotary convertor, the direct current voltage would gradually fall as the load comes on and, in order to counteract this tendency, some method of controlling the voltage must be employed, either by hand or automatically operated. In some cases, it is desired to keep the direct current voltage

constant under all loads, whilst in others a certain amount of variation is desired to meet varying circumstances. The principal methods of voltage control and regulation are (1) reactance control, (2) booster control, and (3) induction regulator control.

REACTANCE CONTROL

In this method the control is effected by introducing reactance in the secondary of the transformer supplying the rotary convertor, or, alternatively, by the introduction of a separate external reactor. The amount of reactance to be installed depends upon the conditions. By this method the applied slip ring voltage is altered without any change taking place in the applied voltage to the transformer primaries. As the load comes on the slip ring voltage is raised and thus neutralizes the inherent drop in the machine itself, resulting in a constant commutator voltage. If desired, a rising direct current characteristic can be obtained.

The manner in which this is brought about is best illustrated by the vector diagram shown in Fig. 8. On light load the rotary convertor works with a weak field, so that the armature current lags by a considerable angle. This is shown in the vector diagram at (*a*), where *OS* represents the applied slip ring volts and *OI* the armature current lagging by an angle ϕ. The voltage required to force the current through the series reactance is given by *OR*, whilst the voltage delivered by the transformer secondary is *OT*, which is the vector sum of *OS* and *OR*. The voltage *OR* is shown leading the current by 90°, the small resistance drop in the reactor being neglected. In Fig. 8, *OT* is assumed to remain constant. When the rotary convertor is working on full load, the field current is strengthened, so that the power factor is raised to unity or thereabouts. This condition is shown at (*b*). The voltage drop in the

reactor is increased, due to the increased current, but the important fact to note is that this voltage OR is still 90° ahead of the current, and is thus considerably in advance of its former position. Since the transformer secondary voltage OT is the same as before, the applied slip ring voltage OS can be found by vector subtraction.

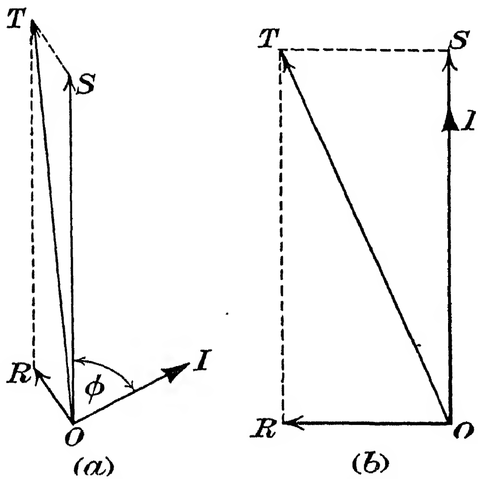


FIG. 8. REACTANCE CONTROL OF ROTARY CONVERTOR

This is now found to be greater than its previous value, the increase being designed to balance the inherent drop. The magnitude of this increase in slip ring voltage is dependent upon two factors: (1) the percentage value of the added reactance, and (2) the change in the power factor. If a large reactor be employed, then only a relatively small change in power factor will be sufficient, but if a smaller reactor be substituted, then a relatively larger change in power factor will be necessitated.

The change in field current can be effected by hand,

but it is much more convenient for this to be done automatically. This is quite easy to arrange by making the rotary converter compound wound, the series coils being in series with the direct current line, so that strengthening of the field takes place automatically as the load increases.

In practice it is found desirable to arrange for the convertor to work on unity power factor at or near to full load, since the armature heating of this type of machine goes up very rapidly as the power factor falls away from unity. A poor power factor is much preferable, therefore, at low loads to what it is at full load.

BOOSTER CONTROL

This method of controlling or varying the direct current voltage consists of inserting an alternating current rotating armature type booster between the slip rings and the convertor armature. This booster increases or decreases the alternating current voltage and so raises or lowers the direct current voltage. By this method the power factor is independent of the load and voltage. This method of control is suitable for cases where a large direct current voltage range is required or where independent power factor control is desired. Convertors controlled by this method are apt to suffer from commutation troubles if not carefully designed.

INDUCTION REGULATOR CONTROL

Instead of inserting a rotating booster between slip rings and convertor armature, an induction regulator is inserted between transformer and slip rings. This induction regulator raises or lowers the voltage applied to the slip rings and so raises or lowers the direct current voltage. The regulator itself is constructed like an

induction motor with stator and rotor windings, one set being connected across the mains and acting as the primary of a transformer, whilst the other set is connected in series with the slip ring circuit and acts as the secondary of a boosting transformer. The rotor of the regulator does not rotate, but is moved into different positions so that the boost voltage, whilst not altering in magnitude, changes in phase with the position of the rotor, and so alters the magnitude of the slip ring voltage, which is the vector sum of the main transformer secondary voltage and the induction regulator secondary voltage.

These regulators are frequently mounted on the rotary convertor itself, being connected between the alternating current brushes and the convertor terminal board. The regulator rotor may be moved either by hand or by means of a small motor which may be automatically operated.

TRANSFORMERS FOR ROTARY CONVERTORS

There is a number of special points to be observed in connection with transformers which are intended for use with rotary convertors. In the first place, as has already been pointed out, all six secondary ends are required for six-phase operation. Tappings for special purposes are frequently required, as in tap starting. Where reactance control is adopted, the reactance is usually provided in the transformer itself by placing small packets of stampings in the path of the secondary leakage flux (but not the primary leakage flux). This obviates the necessity for special choking coils. The latter are, however, desirable if the convertor is also to run inverted (direct current to alternating current), since then they can be short-circuited to avoid additional voltage drop.

THREE-WIRE OPERATION

A direct current three-wire system can be fed from a rotary convertor by connecting the direct current neutral to the star point of the transformer secondaries, which then act as a static balancer in addition to their other functions. For this purpose the mid-point tappings of the transformer secondaries must be brought out and connected together in a star point. These windings now constitute a six-phase star. If only a small out-of-balance direct current is anticipated, then only one secondary need have its mid-point brought out, balancing being carried out on the one winding only. On the other hand, if a very heavy out-of-balance current is to be dealt with, then a separate static balancer should be installed. This consists of a three-phase transformer core with a set of windings connected in zig-zag star.

The commutating poles of rotary convertors intended for three-wire operation should be connected alternately on each side of the system, so as to obtain an average effect.

INVERTED RUNNING

When a rotary convertor is converting from direct current to alternating current, it is running as a direct current shunt or compound motor and its speed is, therefore, dependent upon its field strength. In these circumstances, if it be suddenly called upon to deliver a lagging load there will be set up a demagnetizing armature reaction which will weaken the field and may cause the set to race. For this reason, rotary convertors, which may at times be required to run inverted, are provided with a separate direct-coupled exciter. As the speed rises, the exciter voltage rises and brings about an increase in the field current, thus counteracting

the weakening effect of the lagging alternating current load current.

SPEED LIMITING DEVICE

To prevent accidental racing, large rotary convertors are fitted on the shaft with a speed limiting device which usually consists of an arm operated by centrifugal force against the action of a spring. This arm tends to fly outwards and at the critical speed trips a trigger which closes the tripping circuit of the direct current circuit breaker.

MOTOR CONVERTORS

The motor convertor is a substitute for a rotary convertor together with its bank of transformers, and may be employed in a sub-station of the same type. There are two direct-coupled machines in place of one, thus occupying rather more floor space, but against this there is the saving in room on account of the absence of transformers. This comparison rather favours the rotary convertor, since this may be provided with a rotating booster and exciter or a starting motor either separately or in combination.

Motor convertors can be wound for direct connection to the E.H.T. mains, the only part concerned being the stator windings of the induction motor part of the set. The rotor of this machine operates at a low voltage in any case, the value of this being settled by the direct current voltage required at the commutator.

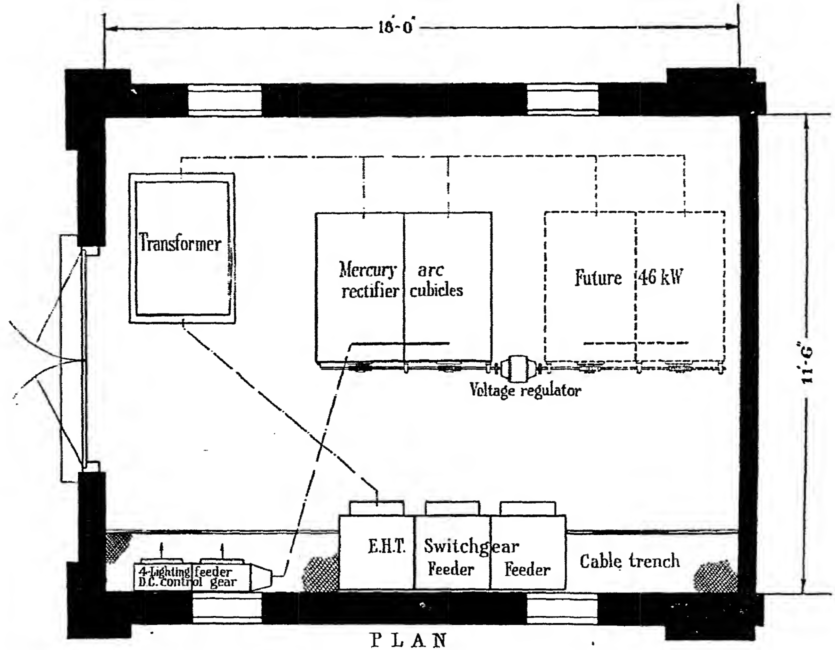
STARTING

Motor convertors can be started from either end, but it is usual to arrange for them to be started from the alternating current end. Although wound for twelve phases, only three or, in the very large sizes, six phases are used for starting. The slip rings connected to these

rotor phases are also connected to a rotor starter which is sufficient to bring the set up to its correct speed, this being much less than the synchronous speed of the induction motor operating by itself. The direct current end is now excited and the rotor circuit becomes affected by two voltages, the first due to the rotor slipping through the rotating field of the induction motor stator, and the second due to the induced voltage in the rotary convertor armature. The frequency of the first is that of slip and that of the second the frequency corresponding to the speed. As these two frequencies approach one another, the rotor current commences to show the phenomenon of beats. A voltmeter is connected across two of the slip rings and the needle of this commences to swing across the scale, the swings gradually getting less in frequency but greater in amplitude. Finally, the set pulls itself into synchronism automatically and the slip rings are short-circuited. At the same time all the other phases are brought into circuit by means of a short-circuiting ring mounted near the slip rings. The set is now ready for running on load.

THREE-WIRE OPERATION

The method of providing for the out-of-balance current in the direct current neutral is very similar to that adopted in the case of rotary convertors. The problem is to get this current back into the armature of the convertor half of the set, at a potential which is midway between those of the brushes. The induction motor half of the set takes the place of the transformer, so that all that is necessary is to take a connection to the star point of the rotor windings. This is effected by connecting the direct current neutral to the slip rings, which are short-circuited when running on load and at star point potential. This connection is made



(I.E.E. Journal)

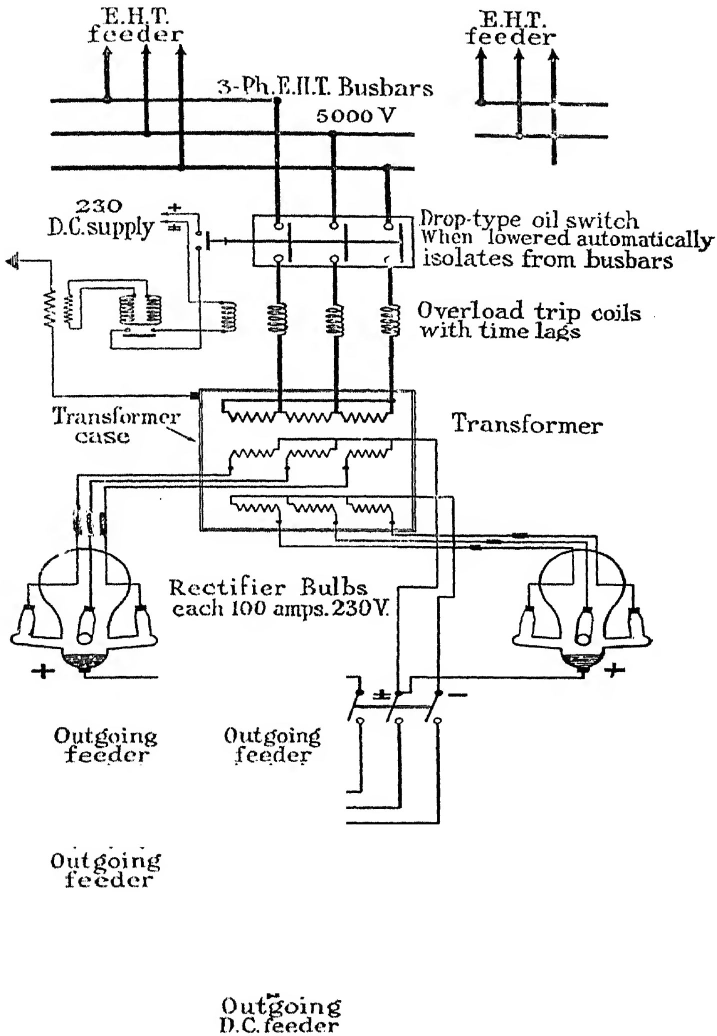
FIG. 9. LAYOUT OF 46 kW THREE-WIRE RECTIFIER LIGHTING SUB-STATION

very simply by means of a triple-pole change-over switch. In one position the slip rings are connected to the rotor starter and in the other they are short-circuited and connected to the direct current neutral.

MERCURY ARC RECTIFIER SUB-STATIONS

The mercury arc rectifier is the only practical rival to the rotary convertor and motor convertor for converting electrical energy from the alternating current to the direct current form, in which rotating machinery is not employed, and even in this case, the statement is not wholly accurate, for there must be provided a vacuum pump set and an ignition convertor for the large all-metal units. This ignition convertor is a small set operating at a relatively low voltage and providing the current necessary for operating the ignition anode. When glass bulbs are employed, these auxiliaries are no longer necessary. All this apparatus must necessarily be installed in some kind of a building, but this need not be of an elaborate character. Mercury arc rectifiers employing glass bulbs are eminently suitable for dealing with a load which demands a large number of sub-stations of relatively small output, where attendance has to be cut down to a minimum.

An example of the layout of such a small sub-station requiring only occasional attendance is shown in Fig. 9. The alternating current supply is brought in through a cable trench to the E.H.T. switchgear, from whence the supply is taken to the transformer, the purpose of which is to reduce the voltage to the value required by the rectifier. Two rectifiers are provided, each in its own cubicle, but space is allowed for the future installation of a further pair of rectifiers. The direct current is controlled by its own switchboard as shown in the illustration. Double folding doors are provided, the



(*I.E.E. Journal*)

FIG. 10. DIAGRAM OF CONNECTIONS OF 46 kW THREE-WIRE RECTIFIER LIGHTING SUB-STATION

opening of which must be sufficient to permit the entry of the transformer and rectifiers.

The diagram of connections of this sub-station is shown in Fig. 10.

The three-phase E.H.T. supply at 500 volts is brought up to the busbars, from whence it passes through an automatic oil switch to the transformer. In these leads are connected the overload trip coils which operate the oil switch. The transformer is provided with double secondaries, each group of which feeds the arc rectifier. The two rectifiers are not intended for independent operation, but must work together for the purpose of supplying a direct current three-wire system. The right-hand ends of one group are connected together to form a star point, which is connected to the direct current neutral, the other three ends going to the rectifier anodes. The corresponding cathode forms the positive of the direct current system. In the same way, the three left-hand ends of the other group of secondaries are connected together, this star point going to the negative, whilst the corresponding cathode which is positive compared with the star point connection, goes to the neutral. The direct current three-wire supply thus being obtained, it is taken away to the outgoing feeder through the necessary switchgear. It is thus obvious that any future rectifiers which may be added must be installed in pairs.

For the larger outputs the all-metal mercury arc rectifier is used in preference to the one employing a glass bulb, and, as with rotary convertors, a six-phase arrangement is adopted. Such a rectifier is started by means of a special ignition anode. This consists of a small central anode on the end of a long rod, held somewhat above the surface of the mercury cathode pool. The upper end of this rod is attached to an iron core which is actuated by a solenoid. When the

pressure is switched on, this solenoid becomes energized and causes the core, rod, and ignition anode to be depressed, against the reverse pull of a spring, until the anode touches the surface of the mercury. The solenoid is then short-circuited, on which the spring pulls the anode away from the mercury. An arc is struck between the retreating contacts, setting up sufficient mercury vapour to cause the main arcs to come into action.

One point about the operation of the mercury arc rectifier is that if the direct current load should disappear, the arcs would be extinguished and the action cease. To prevent this happening, a pair of further auxiliary anodes are introduced for the purpose of supplying current to a small artificial load, the magnitude of which is designed to be sufficient to keep the main arcs in action.

VOLTAGE REGULATION

The direct current voltage can be controlled by step-by-step regulation on the primary side of the transformer, or by an induction regulator which may be automatically operated. Induction regulator regulation is preferable, since it enables the voltage to be varied smoothly, whereas the step-by-step method is apt to be jerky. Furthermore, when the induction regulator is automatically controlled it is possible to leave the sub-station largely unattended.

COMPARISON WITH ROTARY CONVERTOR

In many respects the mercury arc rectifier is superior to the rotary convertor. A higher efficiency is claimed for it, except at low voltages. It has less weight and does not require such costly foundations, particularly as it needs less floor space. There are no running parts, and the wear on the electrodes is surprisingly small.

The rectifier is noiseless in its operation, and so can be erected in crowded areas without complaint. From these considerations it is obvious that the rectifier has a distinct field of usefulness in sub-station work, and installations of this character may be expected in the future in increasing numbers and size.

SECTION XXI

SUB-STATIONS

TESTING, MAINTENANCE AND OPERATION

BY

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SECTION XXI

SUB-STATIONS

TESTING, MAINTENANCE AND OPERATION

SUB-STATIONS

THE maintenance and operation of sub-stations cover a large field, as practically sub-stations range in size from the small kiosk and static transformer sub-station of 100 kVA capacity or less to the large manually operated rotary convertor or motor convertor sub-station of 15,000 kW or more. Some of the transformer stations about to be erected in connection with the "grid" will contain transformers of large capacity.

Sub-stations may be divided into four groups, viz.—

1. Static transformer sub-stations.
2. Manually operated rotary convertor sub-stations.
3. Automatic and semi-automatic rotary convertor sub-stations.
4. Mercury arc rectifier sub-stations.

STATIC TRANSFORMER SUB-STATIONS

As the Electricity Commissioners have standardized a frequency of 50 cycles for the national supply, static transformer sub-stations will become more numerous, not only for rural and residential districts, but also for the supply to large towns and cities.

The maintenance costs of this type of sub-station are much lower than for any type of sub-station for direct current supply, as no continuous attendance is required.

The smallest types of static sub-stations are, first, the pole transformer type used in connection with overhead distribution, and, secondly, the kiosk, which

is not a sub-station within the meaning of the Factory Act, but which serves a useful purpose for low-tension distribution.

Kiosks are usually built of steel or brick, the most popular type being of steel construction. Kiosks so constructed can be transported from the factory to site

FIG. 1. 200 kVA KIOSK

complete with high-tension and low-tension switchgear connected. The size varies according to the capacity and the number of feeders to be housed. The kiosk illustrated in Fig. 1 is designed to take a 200 kVA transformer, three high-tension feeders, and six low-tension feeders. The external dimensions are 8 ft. × 8 ft. × 8 ft. high. A diagram of connections is shown in Fig. 2. There are three separate chambers ; one contains the high-tension switchgear, another the low-tension

switchgear, and a third chamber, situated between the high-tension and low-tension chambers, contains the

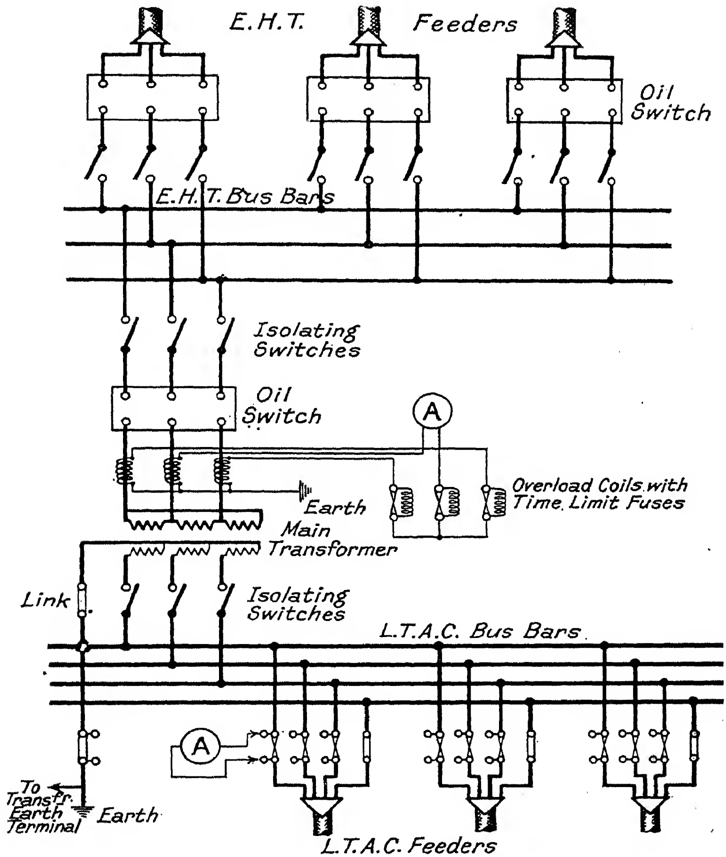

FIG. 2. DIAGRAM OF CONNECTIONS OF 200 kVA KIOSK

transformer. Each chamber is protected by a separate door, which is opened from the outside of the kiosk,

and the high-tension isolators are further protected by a separate door for each set of switches.

When it is desired to discharge a high-tension feeder the operator will open the outer door of the kiosk giving access to the high-tension switches, the oil switch of the particular feeder will be opened, after which the isolating switch door will be opened and the isolating links withdrawn by a special insulated hook. The isolating switch door will then be closed and locked, and the key should be held by the person working on the feeder. If the feeder can be made alive from both ends it will be necessary, of course, to isolate both ends and for the two keys to be held as protection. Sometimes there is a T-joint on the feeder, making it possible to charge the cable from a third point. Care must be taken to isolate the feeder at all points where it is possible to become charged, and no keys should be given up until the job is finished and a thorough inspection made to see that all is clear.

A three-pole air-break isolating switch is connected between the low-tension side of the transformer and the busbars. It is very necessary that this switch should be opened before any work is carried out on the high-tension side of the transformer, even though the high-tension side is isolated, as the low-tension network may be connected to another source of supply, which will feed back into the transformer and step up to the high pressure. Serious accidents have resulted from a failure to take this precaution.

Porcelain handle Home Office pattern fuses are provided on each phase of the feeders, no knife switches being provided. A copper link is connected in each neutral. Plug sockets are connected across each fuse to enable an ammeter having flexible leads to be plugged in to read the load when the fuse is withdrawn. Likewise the leakage current can be measured by connecting

the ammeter across the link in the earth circuit and withdrawing the link. In this way the number of instruments required is reduced to a minimum, one ammeter only being required, which can be mounted on the panel, or, if desired, can be of the portable type so that one ammeter can be used for a number of kiosks. The type of ammeter whose magnet grips round the cable is very useful as a portable instrument on single core cables and on the tails of three-core cables, but, of course, cannot be used on a three- or four-core cable.

The advantage of kiosks, as compared with sub-stations, is that being smaller and cheaper they can be placed at points on the network where most required, that is, they can be placed on the "hot spot" of the load and the distributors taken straight from the kiosk. A number of small kiosks, therefore, suitably placed in the network, is usually cheaper and better than running out low-tension feeders from a larger sub-station centrally placed. For supplying a certain class of load, such as a residential district, it is usually fairly easy to find an odd corner in a garden where a kiosk can be erected. The Home Office Electricity Regulations do not apply to kiosks in respect to adequate gangways, etc., therefore the structure can be small and compact, just large enough to hold the gear required with safe electrical clearances and no more. The kiosk shown in the illustration is for underground cables, but others are constructed to receive overhead mains.

LARGE STATIC TRANSFORMER SUB-STATIONS

For the linking up schemes in connection with the national supply, large transformer sub-stations are required, stepping down the super-tension supply to

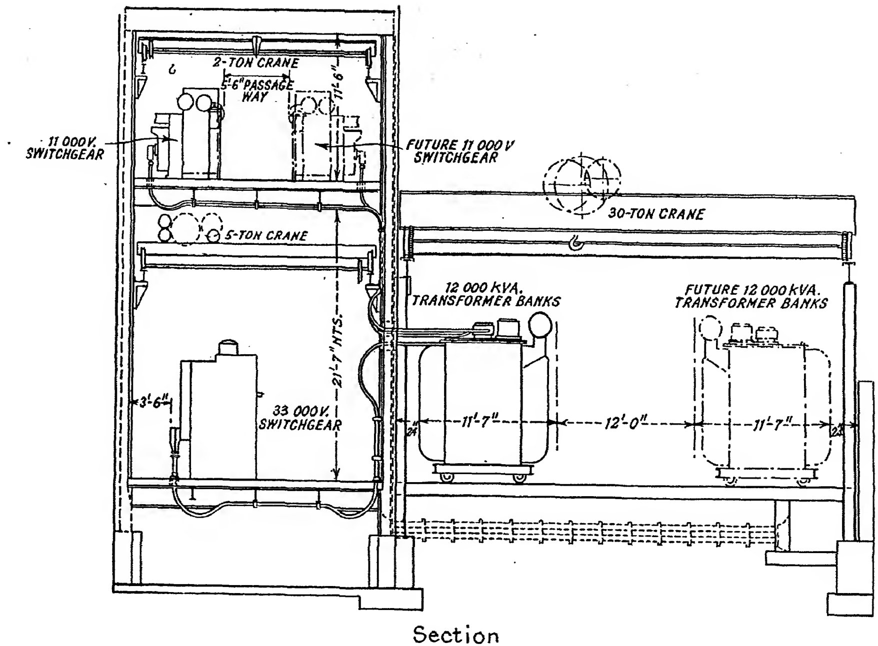

Fig. 3. Layout of Large Static Sub-station

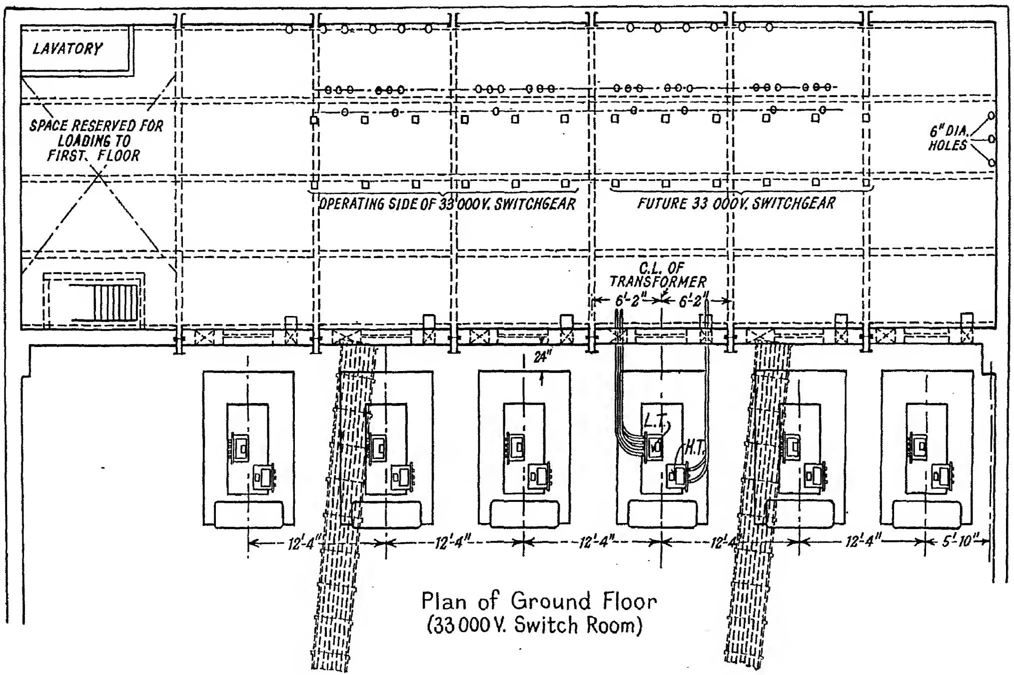

FIG. 3. LAYOUT OF A LARGE STATIC SUB-STATION

E.H.T. A layout of such a sub-station is shown in Fig. 3, which has outdoor type transformers and the switchgear inside the building, cranes being provided for easy handling of all the gear.

The placing of the transformers outside considerably reduces the cost of the sub-station as a smaller building is required.

E.H.T. CONSUMERS' SUB-STATIONS

A large supply authority supplying power to a great number of big works requires a special staff to attend to the small static transformer sub-stations situated on the consumers' premises, and to inspect and test the switchgear installed.

The E.H.T. panels in a consumer's sub-station are shown in Fig. 4. The wide panel on the left is the meter panel containing the metering transformers, and the oil switch and isolators controlling the consumer's supply. The other two panels are the feeder panels, one feeder looping in and out and capable of being fed from either end. The consumer is only allowed to operate the oil switch on the meter panel controlling his supply, the feeder oil switches being locked in. If the consumer wishes to work on his E.H.T. gear, the supply authority will open and earth the isolators on the meter panel, the door of which is locked until the job is finished. When the supply is required again the consumer must request the supply authority to close the isolators. In this way safety is assured, as an earth has been connected between the busbars and the consumer's gear on the isolating switch, and the supply authority knows of all work going on.

The inspection of the feeder oil switches can usually be done by isolating one feeder at a time during working hours, but the meter switch controlling the consumer's supply can only be inspected when the works are shut

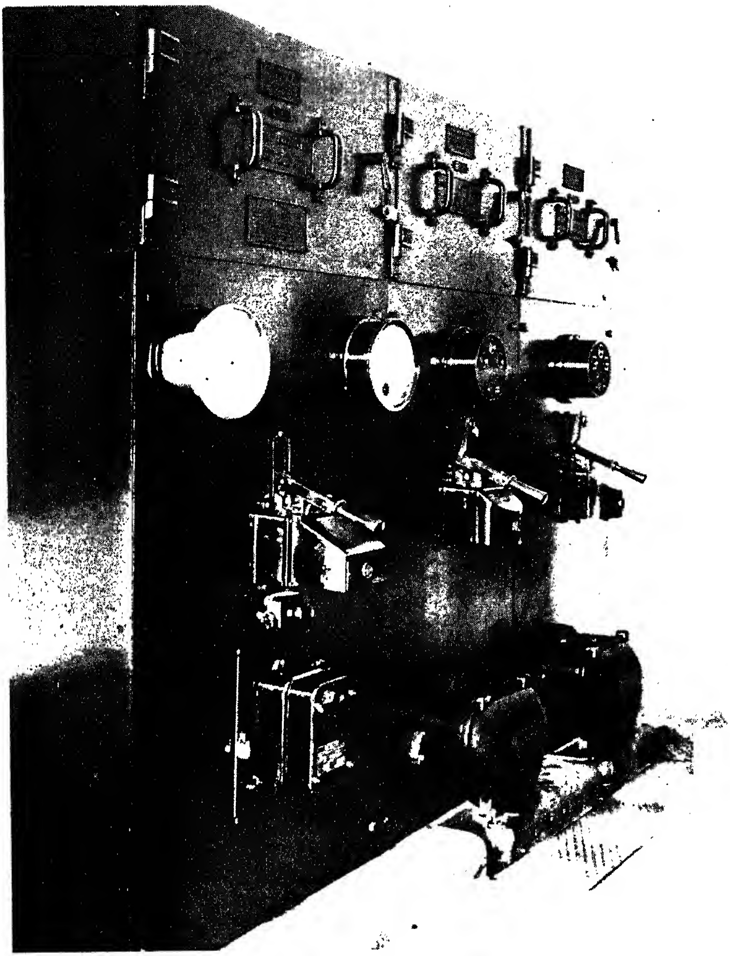

FIG. 4. E.H.T. PANELS IN CONSUMER'S SUB-STATION

down, and this means inspectors continually working week-ends and nights to inspect and test this switchgear.

Overload alternating current trip coils or overload and leakage protection is provided on this switchgear, also a no-volt release. As it is inconvenient to get testing apparatus to consumers' sub-stations for alternating current testing of the trip coils, the test can be carried out by direct current. The trip coils are disconnected from the current transformers and a direct current passed through from a nickel-iron cell with an ammeter in circuit. The alternating current coils will operate at the same value with direct current, and this is a convenient way of testing this class of gear. The no-volt release is tested by withdrawing the potential transformer low-tension fuse when the switch is closed, to make sure the switch will trip if the supply should fail.

The gear in a smaller consumer's sub-station, suitable for 50 to 100 kVA, is shown in Fig. 5, and a diagram of the main connections in Fig. 6. It will be seen that only isolating links are provided for the feeders, there being only one oil switch fuse of the drop tank type controlling the supply to the consumer provided with a no-volt release. The inspection is thus reduced to a minimum, and there is no overload protective gear to test.

MANUALLY OPERATED SUB-STATIONS

The chief factor in the successful running of any sub-station is cleanliness, whether it be machines or switchgear. The plant in manually operated sub-stations has the advantage of receiving the constant attention of the attendants-in-charge and should, therefore, operate with the minimum of trouble. With this object in view the plant should be divided into two,

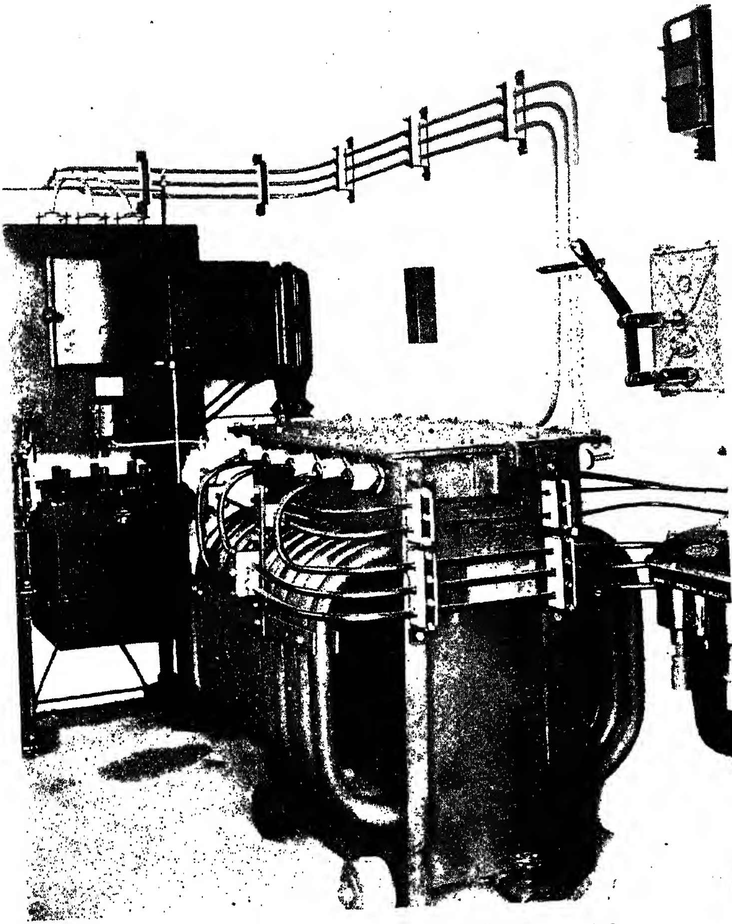

FIG. 5. SMALL CONSUMER'S SUB-STATION

three, or four equal parts, according to the number of shifts worked at that particular sub-station, and each shift should be responsible for the cleaning and general upkeep of one section of the plant. In this way the

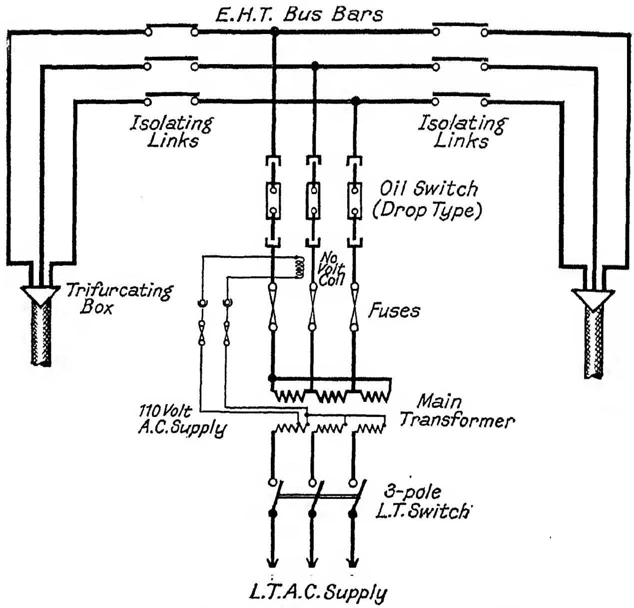

FIG. 6. DIAGRAM OF MAIN CONNECTIONS OF SMALL CONSUMER'S SUB-STATION

attendants-in-charge take a keen interest in their own plant, and do their best to maintain it in good working order.

TESTING OF SWITCHGEAR

The inspection and testing of switchgear should be done by competent switchgear inspectors, who visit each sub-station in turn and thoroughly overhaul the switchgear and test the automatic relays and tripping

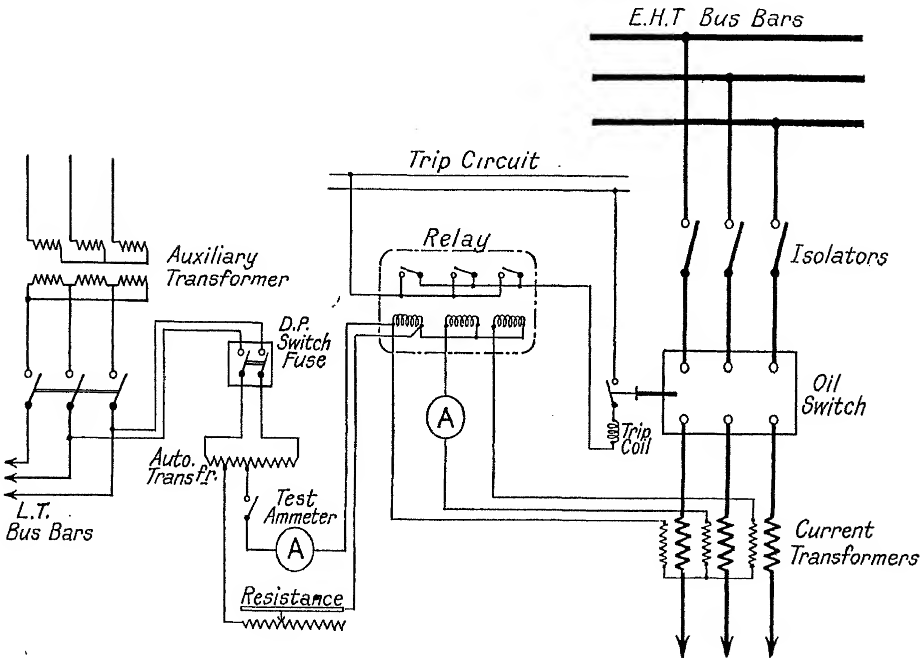

FIG. 7. CONNECTIONS FOR RELAY TESTING ON THE SECONDARY SIDE OF CURRENT TRANSFORMERS

devices in connection with the protection of feeders, transformers, machines, etc.

The testing of overload relays and trip coils may be done by applying a single-phase current to the relay terminals at low voltage. The alternating current supply for the test can usually be obtained from an auxiliary transformer or auto-transformer in the sub-station. A diagram of connections for such a test is shown in Fig. 7. The relays should be tested on all settings, so that any setting can be used as required. Whilst this test shows that the relay and trip coils are working satisfactorily, it will not indicate an open circuit on the wiring or current transformers, but it will show if the secondary turns on the current transformers are shorted. A more satisfactory test, and one that should be carried out wherever possible, is to pass a current through the primary winding of the current transformers. This will not only check the relay, but also the current transformers and the whole of the wiring. It is desirable to have a special portable testing transformer for this purpose to step down from a convenient primary pressure to 4 or 6 volts, the current output, of course, depending on the size of gear to be tested. A diagram of connections for this test is shown in Fig. 8.

Wherever possible it is advisable when making relay tests to clamp the test leads to the current transformer connections, and not disturb any of the permanent cabling or small wiring. In this way the test can be carried out very nearly under working conditions, and there is less risk of any small connections being left disconnected. In order to read the current a test ammeter will have to be connected, either in the secondary or primary circuit of the current transformers. If connected in the secondary circuit a connection will have to be taken off the relay for inserting

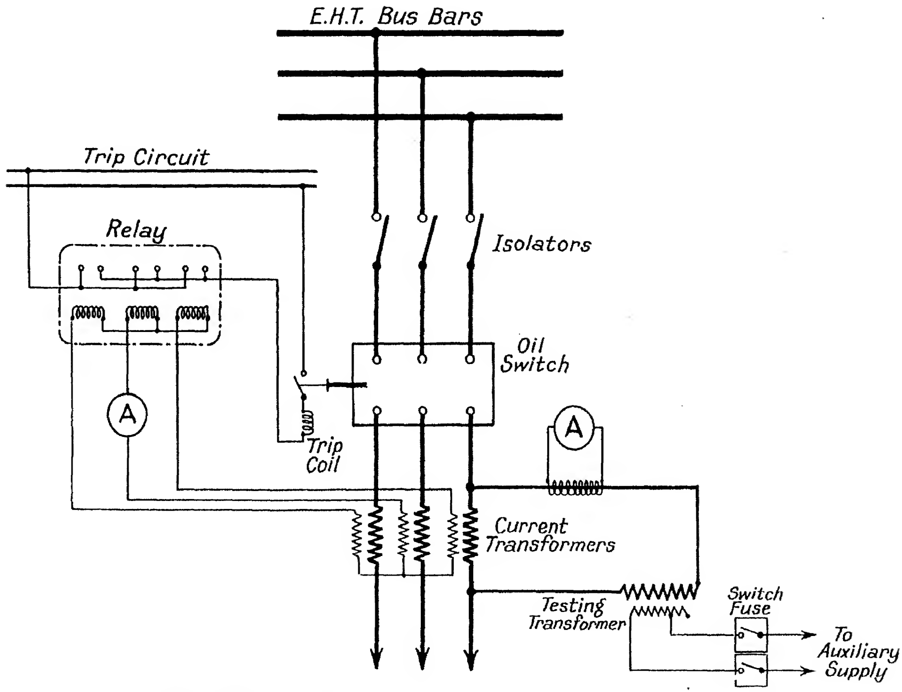

FIG. 8. DIAGRAM OF CONNECTIONS FOR RELAY TESTING ON PRIMARY SIDE OF CURRENT TRANSFORMERS

the ammeter, which, as previously stated, is undesirable. A current transformer is, therefore, connected in the main test circuit for the purpose of connecting the ammeter to read the main current. In this way it is absolutely unnecessary to disconnect any permanent lead whatsoever.

If loose current transformers are available of suitable

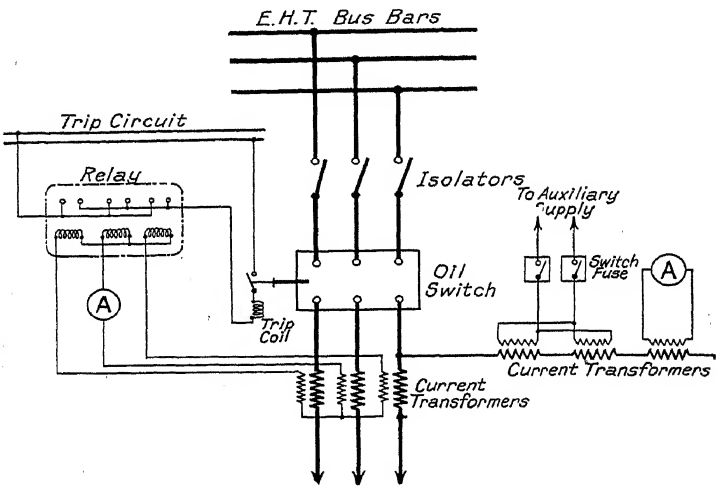

Fig. 9. Diagram of Connections for Testing with Three Current Transformers

capacity they may be used instead of the special testing transformer, if connected as shown in Fig. 9, with the secondaries in parallel and the primaries in series. It will be clear from the diagram that the third transformer is used for the ammeter only.

Where double-pole relays are used for overload protection on three-phase systems, with the three current transformers connected in "Z," the initial test should be made on the primary side of the current

transformers to check the connections, for if one of the coils is connected to the reversed phase of the current transformers which carries $\sqrt{3}$ times the current in the other leads, the relay will operate prematurely on load, although the setting of the relay when tested direct appears to be correct. Fig. 10 shows "Z" connected current transformers connected so that $\sqrt{3}$

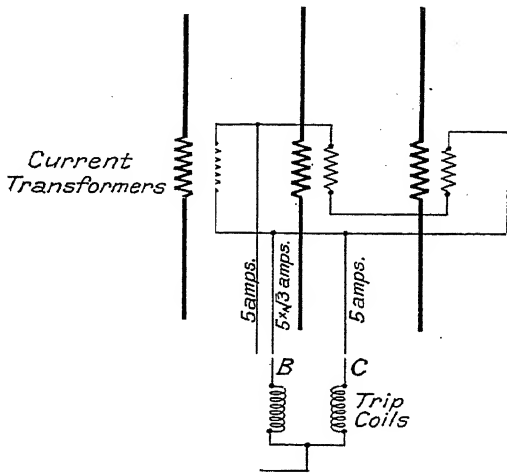

FIG. 10. DIAGRAM SHOWING Z-CONNECTED CURRENT TRANSFORMERS INCORRECTLY CONNECTED TO TRIP COILS
Leads *A* and *B* are crossed

times the normal current passes through the left-hand trip coil due to leads *A* and *B* being crossed. This excess current will not, of course, be present in a single-phase test, but the value of testing from the primary side is that should the connections be reversed, as indicated in Fig. 10, both trip coils will operate when the test current is applied to the right-hand phase, and only one coil will operate when the test current

is applied to the middle phase. If the secondary connections are traced out, it will be found that when connected properly both relay coils are in series when testing from the transformer on the middle phase, and only one coil is in circuit when testing either of the other two phases. It is obvious, therefore, that if the two relay coils operate when testing either of the outer phases, there is a cross connection. A case illustrating this came under the author's notice, where a rotary convertor had been in service for a number of years without trouble until a little more load than usual was put on the machine, when the relay operated and shut down the machine. A test was made direct on to the relay and the setting was found to be correct. The rotary was put on load again with the same result, that the relay operated at about half its setting. A test was then made from the primary side of the current transformers, and still the relay operated at the correct setting, but both relay coils operated when testing one of the outer phases which indicated that there was a cross connection, as both coils should have operated only when the middle phase was being tested. This is mentioned to emphasize the fact that although single-phase testing of three-phase circuits is convenient, it is necessary to determine beforehand whether the single-phase test values represent the actual three-phase working. With the "Z" connections incorrectly made they do not, but the fact that both coils operate when only one should do so indicates that there is a wrong connection, which can soon be traced. The particular relay referred to had been tested many times before from the secondary side of the current transformers and had operated at the correct setting, but it was not until trouble had been experienced by the machine shutting down that further investigations were made, and then the single-phase test from the primary side

clearly showed where the trouble lay. After the connections were put right the ammeter readings for the single-phase test represented the normal three-phase working.

ARMOUR-CLAD SWITCHGEAR

When armour-clad switchgear is used the problem arises of how to connect the test leads across the transformer primaries, as the whole gear is totally enclosed and compound or oil filled. This difficulty has been overcome on one class of switchgear by strengthening up the potential transformer connections to the full capacity of the switch and plugging-in the test leads to the potential transformer spout mouths, after the potential transformer plugs have been withdrawn. The potential transformer leads are connected to the opposite side of the current transformer to the main outgoing cables, so that by plugging-in one test lead to the spout mouth connected to one phase of the outgoing cables, and the other test lead to the spout mouth of the potential transformer on the same phase, a connection is made across the primary side of the current transformer through which the testing current may be passed.

It is necessary to bridge the small wiring connections, and for this purpose special plugs are wired up to bridge over from the plugs on the switch carriage to the corresponding sockets when the switch is racked out. A photograph of an armour-clad switch, with a 5 kVA testing transformer connected up by means of these special plugs, is shown in Fig. 11. A set of plugs in case complete is shown in Fig. 12.

TESTING MERZ-PRICE GEAR

The various types of balanced voltage and balanced current systems for feeder and transformer protection

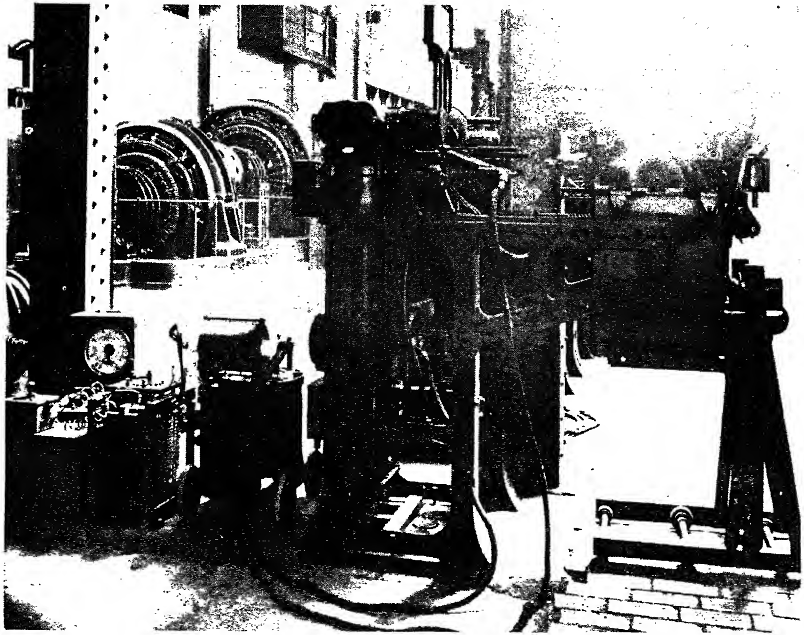

Fig. 11. Armour-clad Switch
Showing testing transformer connected up to the spout mouths

can usually be tested by upsetting the balance of the system in some way, such as short circuiting one or more of the protective current transformers and applying a three-phase current to the gear from an auxiliary

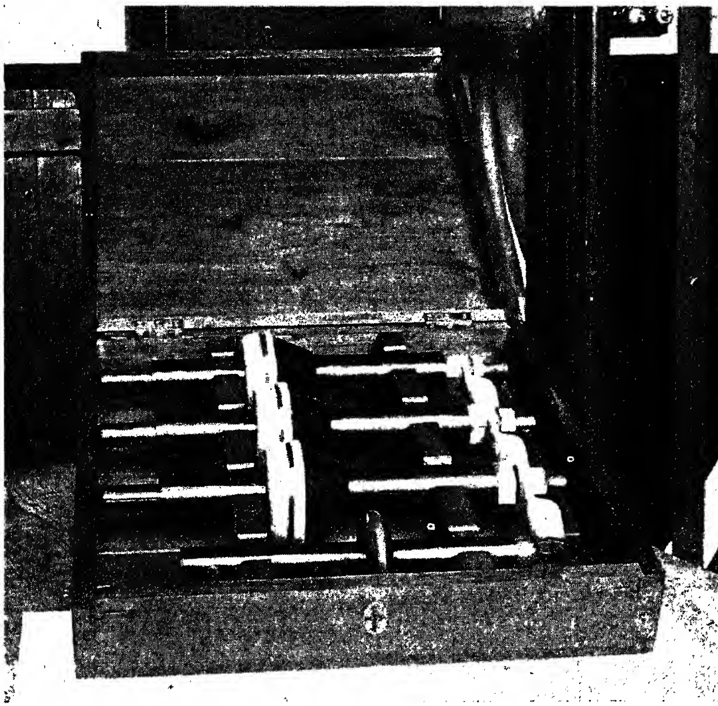

Fig. 12. A Set of Plugs for Testing Armour-clad Switchgear

source. The amount of such current required to operate the relay is the value of the fault current that will operate the relay at that particular setting.

Take the case of an E.H.T. feeder running from a

generating station to a sub-station, which has Merz-Price balanced voltage protection. If the current transformers are short-circuited at the sub-station end by strapping all three phases together on the feeder side, and a three-phase current is applied to the feeder at the generating station end, the voltage balance will be upset, as there will be no current passing through the primary of the current transformers at the sub-station end. Hence a current from the generating station transformers will circulate through the pilot wires and operate both relays, due to the fact that the current transformers at the sub-station are not generating a current in the secondary windings equal and opposite to the secondary current of the transformers at the generating station. It is very convenient, if it can be easily arranged, to run up a generator on the feeder for this test, as the current can then be gradually increased until the relays operate at their fault setting. Fig. 13 shows a diagram of connections for this test.

SPLIT CONDUCTOR PROTECTION

The testing of split conductor protective gear may be done by single-phase current applied to the primary of the current transformers. The primary windings of the transformers are split into two halves wound in opposite directions on the core, so that with equal currents flowing there is no current in the secondary winding. Under fault conditions the currents in the two halves are unbalanced, causing a current to flow in the secondary winding which operates the relay. A small current of about 30 amp. only is necessary for testing purposes, the current being passed through one half of the primary winding. This will induce a current in the secondary winding, and the current at which the relay operates will represent the leakage current under

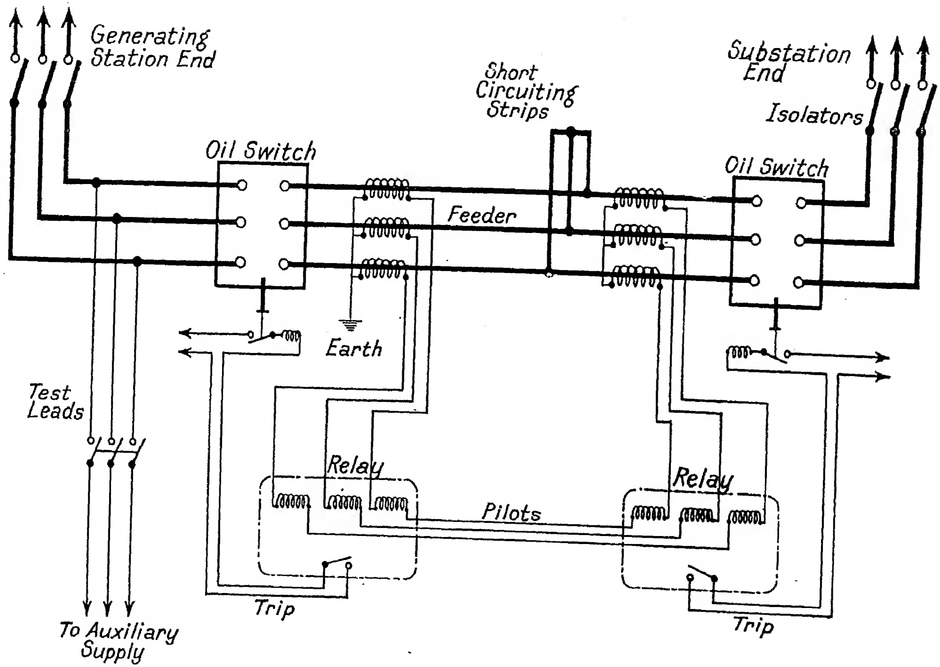

FIG. 13. DIAGRAM OF CONNECTIONS FOR TESTING MERZ-PRICE FEEDER PROTECTIVE GEAR

fault conditions at which the feeder will trip. A diagram of connections is shown in Fig. 14.

In order to ensure the switches tripping at both ends of the feeder on the occurrence of a fault, it is necessary that the two halves of the conductor should remain separated through the oil switch, and to enable this to be done the contacts on each phase on the feeder side of the oil switch are divided into two halves, insulated from each other, i.e. there are six terminals and contacts on the feeder side. On inspecting the oil switch it is necessary to test between these split contacts with a megger to ensure that the insulation is intact. The two halves of the contact, being necessarily very close together, are liable to touch. Any fault found in this direction should be rectified. Also, the mechanical adjustment of these split contacts requires careful attention, for when closing the switch, if the line is alive from the other end and one contact touches before the other, current will flow through half of the winding of the current transformers and operate the relay. It is necessary, therefore, to adjust the auxiliary contacts so that the split contacts are bridged a little in advance of the contacts closing on the busbar side of the switch. Unless the contacts are carefully adjusted it will be impossible to close the switches on to load.

INSPECTION OF HIGH-TENSION SWITCHGEAR

Oil switches should be inspected periodically, and always after a switch has opened on heavy current due to the operation of the protective gear. The tanks should be lowered and the contacts inspected. It will generally be found that the auxiliary sparking contacts are more or less burnt after the switch has opened on a heavy fault, in which case the contacts should be renewed or cleaned up. Inspection should be made of

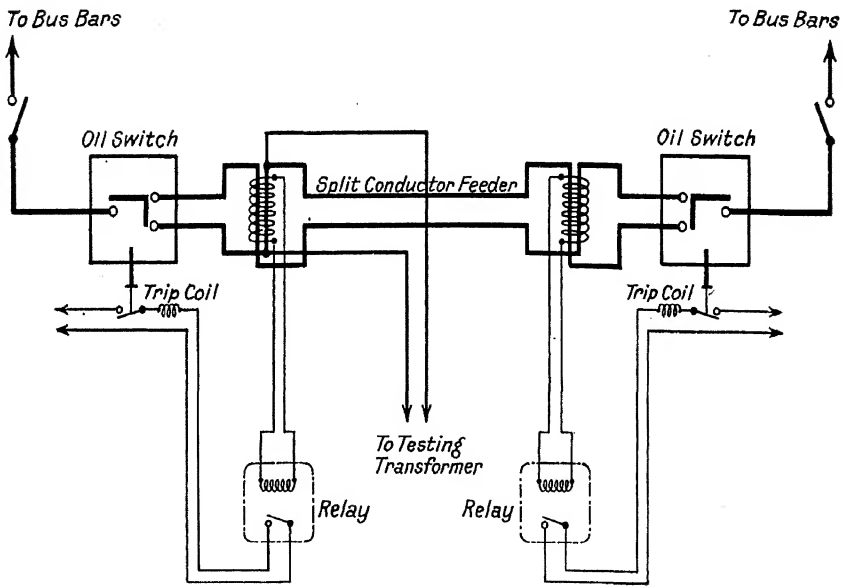

Fig. 14. Diagram Illustrating the Method of Testing Split Conductor Protective Gear

the main contacts to see if they are bedding properly, and they should be tested with a feeler gauge. The auxiliary contacts should make before, and break after, the main contacts. If the auxiliary contacts are not carefully adjusted, pitting of the main contacts will occur.

The condition of the oil should be noted, and if it is at all carbonized, sludged, or found to contain moisture, it should be changed. A rough test for moisture is to draw off a sample of the oil and plunge a red hot rod into the sample. If moisture is present a sharp crackling noise will be heard.

It is sometimes found that the copper contacts in the oil switch blacken, due to sulphur being present in the oil. This can be tested by dipping into the oil a piece of copper with a highly polished surface. The presence of sulphur will quickly oxidize the copper. It will generally be found that the sulphur has got into the oil from the cement used to fix the insulators, which sometimes consists of a mixture of sulphur and glass that is softened by the oil. Where this class of cement is used, care should be taken to see that it is well above the oil. It is essential that the insulators be kept clean and free from cracks. Where it is difficult to see at the back of the insulators, a small mirror will be found useful. The mechanical parts of the oil switch should be well lubricated and the hold-on catches examined. It should be impossible for the switch to trip out by vibration or an accidental knock on the handle. This should be tested by bumping the handle several times, and if the switch should jar out, attention must be given to the hold-on catch.

When inspecting a switch all connections should be examined, and those that are taped up should be undone for that purpose.

Busbars and isolating switches can only be inspected

when the sub-station can be made dead and arrangements should be made at least once a year for this to be done. This usually entails a lot of outside switching to keep the consumers alive from other sources of supply. If busbar section switches are installed the work is simpler, as one section can be made dead at the time. When a job of inspecting high-tension gear is going on, the man in charge of the work should hold the keys of all isolators protecting the particular apparatus.

SUB-STATION STAFF ORGANIZATION

In a large electricity supply undertaking the work is so varied in character that it is necessary for the management to be split up into a number of departments, each controlled by an engineer who has specialized in a particular branch of electrical engineering, each of course responsible to the chief engineer. It is the object of the author to describe briefly the staff organization and various aspects of the work in connection with the sub-stations department of a large electricity undertaking.

Where constructional work is carried out by the department this work is sometimes supervised by an engineer responsible for the constructional work alone, who is entirely separate from the running and maintenance staff.

Fig. 15 shows a chart of a typical sub-station staff organization. The sub-stations engineer has a chief assistant, who deputises for the sub-stations engineer, under whom are the assistant engineers responsible for certain sections of the work or groups of sub-stations. Thus one assistant is responsible for the maintenance and constructional work of the manually operated sub-stations. Another takes charge of the maintenance and operation of the E.H.T. consumers' sub-stations.

The automatic sub-stations and the mercury arc rectifier sub-stations are grouped together, but the maintenance is carried out by one assistant and the constructional work by another. The actual responsibilities vary with different undertakings, but the scheme shown on the chart in Fig. 15 may be taken as typical of the staff organization of the sub-stations department of a large electricity undertaking.

Taking first the manually operated sub-stations, the assistant responsible for the maintenance and constructional work has under him inspectors or junior assistants, who may each be responsible for the whole of the work in a certain number of sub-stations or for certain sections of the work, such as plant maintenance, new constructional work or switchgear. Next come the attendants-in-charge of a sub-station and assistant attendants, who work rotating shifts and are generally known as shift men. The day men are the battery attendants, switchgear inspectors, fitters, wiremen, etc., who work the usual hours.

DUTIES OF SHIFT MEN

The attendants-in-charge are responsible for—

1. Maintenance of supply.
2. Starting up and shutting down machines.
3. Economical running of plant.
4. Normal charging of batteries.
5. Keeping a correct log of the load and happenings in the sub-station.
6. Routine testing, such as "Megger" test of insulation resistance of plant, traction leakage test and lighting leakage test, testing alarm circuits, etc.
7. Attending to all recording instruments—inking pens, changing and labelling charts.
8. Cleaning of switchboards.
9. Cleaning machines and transformers.

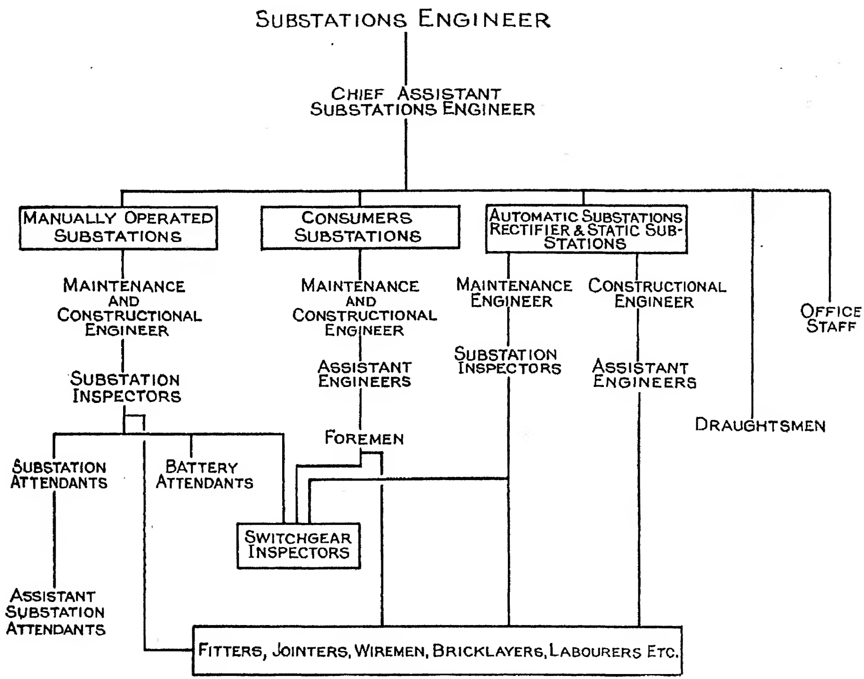

FIG. 15. ORGANIZATION STAFF CHART OF SUB-STATIONS DEPARTMENT OF A LARGE ELECTRICITY SUPPLY UNDERTAKING

10. Attending to commutators and bedding brushes of machines.

The assistant sub-station attendants work to the instructions of the attendant-in-charge, and at sub-stations where no cleaner is kept the assistants are expected to keep the floors, walls, and stairs clean and also to stoke any fires.

The attendant will use his discretion when to start up and shut down machines. The load in some sub-stations has to be anticipated, especially in industrial areas, where the majority of works shut down for the lunch hour at a certain time. It is necessary for enough plant to be available for load on the resumption of work, as under these circumstances the load comes on very rapidly.

Unless there is sufficient spare plant to justify putting machines out of commission in the day time, the attention to brush gear and commutators will have to be given on the night shift, when the load is usually light and the machines can be shut down for cleaning. The men will also be less occupied on the switchboard. On the other hand, where the load allows of some machines being shut down in the daytime, there is no doubt that they will get better attention than at night.

REPORTING BREAKDOWNS

With regard to the operation of the E.H.T. feeder switches and busbar section switches, the attendant will only operate these to the instructions of the control engineer, or, as this official is called in the U.S.A., the load dispatcher, whose duty it is to control the E.H.T. switching arrangements and loading of the whole of the system. The control engineer is usually situated in the control room of the main generating station. He has before him a large diagram on which are marked

all E.H.T. feeders and switches on the system, including the main switches in consumers' premises. When any E.H.T. switch is opened or closed the diagram is altered accordingly by means of small tallies or coloured buttons. The diagram thus shows the position of any switch on the system at a glance. If a high-tension feeder at a sub-station trips out, the sub-station attendant will immediately inform the control engineer by telephone, there usually being a special telephone in each sub-station connected direct to the control room. If there has been no serious disturbance of the system, the attendant will be instructed to set the protective relay light and reclose the feeder switch. If the switch should trip again on closing the attendant must judge, by the swing of the ammeter pointer, whether the tripping is due to normal overload or to a fault and report to the control engineer, who will decide what switching is to be done to maintain supply.

An attendant-in-charge of a manually operated sub-station is not usually expected to carry out any important repairs. He must, however, see that all low-tension connections are tight and tighten up any that have worked loose. If the plant is being constantly cleaned, loose connections will be observed and can be tightened up before giving serious trouble. Especially is this so of the connections at the back of switchboards, where a loose connection to a relay or trip coil, if not found in time, may have serious results. The importance of this is mentioned in the automatic sub-station notes, where the need of inspection and cleanliness is even more important. Any defect in the plant should be entered in the log book, and a copy of the log book entries, together with load readings and recorder charts, sent in to head office every morning. Any serious defect should be reported at any hour of the day or night by telephone.

EMERGENCY CALLS

Some supply authorities employ sub-station inspectors on shift, there always being an inspector on shift at the head sub-station to deal with emergency calls. It is more usual, however, for the attendants at the head sub-station to act as advisors to the other sub-stations after office hours, and to use their discretion as to whether or not it is necessary to bring an official out to attend to the matter immediately. For this purpose a notice should be posted in the sub-station giving the names and addresses of officials to be called out in case of emergency. The list should state first, second, and third call and be altered weekly so that certain of the staff take first, second, and third call in turn, and know when they are more likely to be called out.

SHIFT ARRANGEMENTS

Previous to the war, shift men worked seven days a week, or six eight-hour shifts, and twelve hours on Sunday for two weeks, with every third Sunday off. Now, however, 48 hours constitutes a normal working week. Shiftmen, therefore, working eight-hour shifts must have one clear day off every week. Where sub-stations can be shut down on Sundays this is easily arranged, but where continuous rotating shifts are worked extra attendants and assistants have to be employed. In large sub-stations a fourth shift is worked called the spare shift. The men on this shift usually work from 9 a.m. to 5 p.m., cleaning and attending to the plant, whilst the attendant on normal shift looks after the running. When, however, a man has a day off the spare shift is dropped, and the attendant on this shift will take the place of the man away. Table I gives a suggested four-shift arrangement, where the man on the spare shift "D" takes the place of the

man away from the 3–11 shift "C" on Monday and Tuesday, and the 7–3 shift "A" on Wednesday. On Thursday, Friday and Saturday the spare shift overlaps the 7–3 and 3–11 shifts. The cycle thus lasts four weeks, and as 12 hours are worked on two Sundays, there are two clear Sundays off and one long week-end on the 3–11 "C" shift.

TABLE I

	A Shift	B Shift	C Shift	D Shift
Sunday . .	a.m. p.m. 11–11	p.m. a.m. 11–11	Off	Off
Monday . .	7– 3	11– 7	Off	p.m. 3–11
Tuesday . .	7– 3	11– 7	Off	3–11
Wednesday . .	Off	11– 7	p.m. 3–11	a.m. p.m. 7– 3
Thursday . .	7– 3	11– 7	3–11	9– 5
Friday . .	7– 3	11– 7	3–11	9– 5
Saturday . .	7– 3	11– 7	3–11	9– 5

TABLE II

SUGGESTED THREE-SHIFT CYCLE WITH SPARE MEN WORKING BETWEEN TWO SUB-STATIONS

	No. 1 Sub-station			No. 2 Sub-station		
	A Shift	B Shift	C Shift	A Shift	B Shift	C Shift
Sunday . .	a.m. p.m. 11–11	p.m. a.m. 11–11	Off	a.m. p.m. 11–11	p.m. a.m. 11–11	Off
Monday . .	7– 3	11– 7	Off	7– 3	11– 7	3–11
Tuesday .	7– 3	11– 7	Off	7– 3	11– 7	3–11
Wednesday .	Off	11– 7	3–11	7– 3	11– 7	3–11
Thursday .	7– 3	11– 7	3–11	Off	11– 7	3–11
Friday . .	7– 3	11– 7	3–11	7– 3	11– 7	Off
Saturday .	7– 3	11– 7	3–11	7– 3	11– 7	Off

Where, however, sub-stations can be grouped in pairs, an attendant and assistant can be regularly employed between the two sub-stations working in place of the men standing off. Thus Table II shows a suggested arrangement of a three-shift cycle for a pair of sub-stations.

It will be noted that sub-station No. 1 has a long week-end off on the "C" shift, whereas sub-station No. 2 has Sunday, Friday, and Saturday off on the same shift. In order to equalize matters sub-station No. 1 will work the following three weeks the arrangement shown for No. 2 sub-station, and vice versa. Thus each man will have a long week-end off, i.e. Sunday, Monday, and Tuesday every six weeks. The spare men will thus work at No. 1 sub-station, Thursday 7–3, Friday and Saturday 3–11, Sunday off, Monday and Tuesday 3–11, and Wednesday 7–3. On Thursday 7–3 they change over to No. 2 sub-station and work the same shifts. The spare attendants work more 3–11 than 7–3 shifts, but this is compensated for by having every Sunday off and no night shift. It will thus be seen that with this suggested arrangement the shifts are worked in the following order 11–7, 3–11, and 7–3. The same arrangement could be worked with the hours slightly modified, say, 12–8, 4–12, and 8–4; also the order of the shifts could be different, in which case the change-over arrangements from one shift to another would be modified.

BATTERY ATTENDANTS

The duties of the battery attendants consist of taking regular tests on the batteries, and for this purpose they visit each sub-station at least once a week to take specific gravity and voltage readings of the cells during charge and discharge, also to give the battery the correct amount of overcharge necessary to maintain

it in good condition. The battery attendant will also clear the cells of likely short circuits between the plates caused by the growth of the active material of the plates, top up the cells with distilled water, clean the containers and spray arresters, oil the tops of the containers to stop creepage of acid, boost up any low cells, and generally keep the battery in good condition. Records of specific gravities and cell voltages before and after charge to be entered up and sent to head office; also a record of overcharges should be kept and an account of the treatment given to backward cells.

Where batteries have to be replated this is done by battery attendants if they are also lead burners, which is not always the case. In the latter case the job is usually put out to contract.

SWITCHGEAR INSPECTORS

A switchgear inspector must be a good electrical fitter, and at the same time have a good theoretical knowledge in order to be able to adjust and repair the switchgear; also to test the relays in connection with the various protective devices met with. Modern E.H.T. switchgear with the various forms of protection is very complicated, and only the best men are put on this work, as the failure of a large switch to trip in case of a fault may have serious consequences. In the case of the automatic sub-stations, the switchgear inspectors have to attend to even more complicated gear, and it is usual in this case to have staff men for the job. This will be dealt with more fully elsewhere in this section under "Automatic Sub-stations."

Reports are sent into head office by the switchgear inspectors on special sheets printed for the purpose, giving condition of contacts, mechanical working, etc., of the switches and particulars of relay tests. These

are compared in the office with previous tests and filed for reference.

DUTIES OF ASSISTANT ENGINEER (IN CHARGE OF CONSUMERS' SUB-STATIONS AND STREET KIOSKS)

The engineer responsible for the consumers' sub-stations on a large undertaking usually has a vast area to cover, for where main sub-stations may be counted by the dozen the consumers' sub-stations and street kiosks are in hundreds. It is true that they are very small and contain little plant as compared with the main sub-stations, but they have to be attended to. For every new E.H.T. consumer a new sub-station is required, and the engineer in charge of this work has to interview the prospective consumer and arrange the position and size of the sub-station to suit the consumer's requirements. After this, lay-out drawings are prepared and submitted for approval. The installation of the switchgear and plant has to be superintended and tested. The same applies to the erection of kiosks for local supply. Generally, most consumers' sub-stations and street kiosks are also switching points, and all outside switching of the E.H.T. mains has to be arranged by this engineer, who keeps in close touch with the control engineer for this purpose. In addition to the normal switching, there are consumers' isolations to attend to, when consumers require their E.H.T. gear dead for overhaul, which is generally at holiday time or week-ends. Also fire brigade calls, which have to be attended to immediately in case of fire, to cut off the supply to the consumer's premises.

Records are kept giving particulars of switchgear and plant in consumers' sub-stations; also records of tests and inspections in order that these may be carried out in a systematic manner.

Junior assistants, working to the instructions of the engineer responsible, are necessary ; also one or more foremen to supervise the workmen.

DRAWING OFFICE

The draughtsmen in the drawing office of the sub-station department are usually under the direct supervision of the sub-stations engineer and his chief assistant. They are chiefly engaged in preparing plans for new sub-stations and extensions, also preparing drawings and keeping diagrams up to date.

RECORDS

Formerly, when the output of sub-stations was smaller, it was the practice to have watt-hour meters on all feeders, both incoming and outgoing, high-tension and low-tension. The actual low-tension output, efficiency, and load factor of machines was then easily determined. With the larger outputs and multiplicity of feeders in sub-stations at the present time, the trend is to reduce the number of watt-hour meters in the sub-stations. It is usual to have watt-hour meters on the incoming E.H.T. feeders and in some cases on the outgoing E.H.T. feeders. On the direct current side the best arrangement for metering the traction output is to have summation watt-hour meters in the negative busbar, i.e. two or three meters in series, each integrating the total traction output, the average reading of the meters to be taken as the total output. All watt-hour meter readings are taken at midnight, and the units calculated for the day, together with the machine load factors, etc.

Where no watt-hour meters are installed on the low-tension lighting feeders, in the case of manually operated sub-stations, the machine ammeter readings

are plotted against time on squared paper, and the output calculated with a planimeter.

Surprisingly accurate results are obtained in this way, provided the readings are carefully taken. The drawing of the graphs is usually done at the office, although it is the practice on some undertakings for the attendants-in-charge to work the units out in this way on the night shift. The formula for working out the units from the planimeter reading is—

$$P \times E \times k = \text{B.O.T. units}$$

where P = planimeter reading,

E = average busbar volts,

k = a constant depending on the planimeter setting and the scale used. This is easily determined by running the planimeter over a square of known area and checking the reading.

Fig. 16 shows a graph in which the ordinates are ammeter readings plotted against time as the abscissae. The output of automatic sub-stations is usually measured by an integrating watt-hour meter or recording ammeter in each machine or rectifier circuit. When a recording ammeter is used the output in B.O.T. units may be obtained by using the planimeter direct on the chart, there being no need to replot on to squared paper. A typical load chart is shown in Fig. 17.

Readings and log sheets are sent in from the manually operated sub-stations every day, being posted soon after midnight, which usually allows for delivery to head office by first post the same morning. In the case of the automatic and rectifier sub-stations, which are unattended, the visiting attendants send the charts in usually once a week.

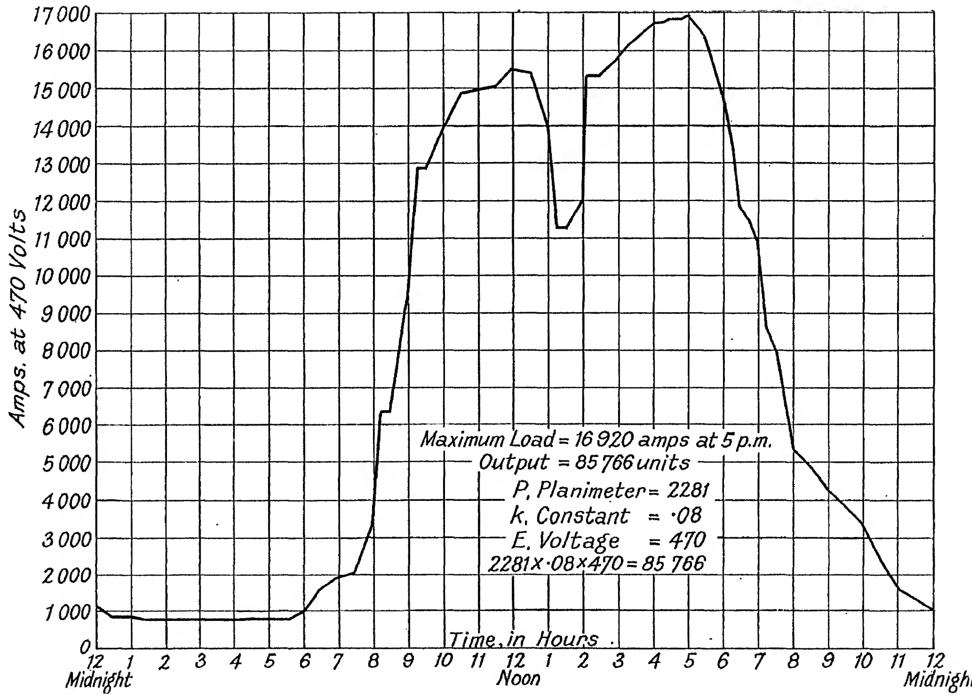

Fig. 16. Lighting and Power Load Curve

The following list gives some idea of the records usually kept—

Capital costs of plant, buildings, land, etc.

Costs per unit output of manually operated sub-stations.

Costs per unit output of automatic sub-stations.

Costs per unit output of mercury arc rectifier sub-stations.

Costs per unit output of static sub-stations.

Plant maintenance records.

Switchgear and relay test records.

Plant insulation resistance test records.

Traction records of earth return current, line leakage, rail points, differential earth potentials, etc.

Also the following outputs, losses, etc., are calculated daily, monthly, and annually for each sub-station—

LIGHTING AND POWER.

- Output.
- Maximum load.
- Machine load factors.
- Machine efficiencies.
- Losses in feeder boosters, balancers, battery boosters, fans, station lighting, etc.
- Peak load feeder readings.

TRACTION.

- Output.
- Maximum load.
- Machine load factors.
- Machine efficiencies.
- Sub-station load factor.
- Peak load feeder readings.

BATTERIES.

- Charge and discharge, ampere-hours.
- Percentage overcharge.

E.H.T. SUPPLIES.

- Trunk feeders—
  - Maximum loads.
  - Daily inputs.
- Outgoing feeders—
  - Maximum loads.
  - Daily outputs.

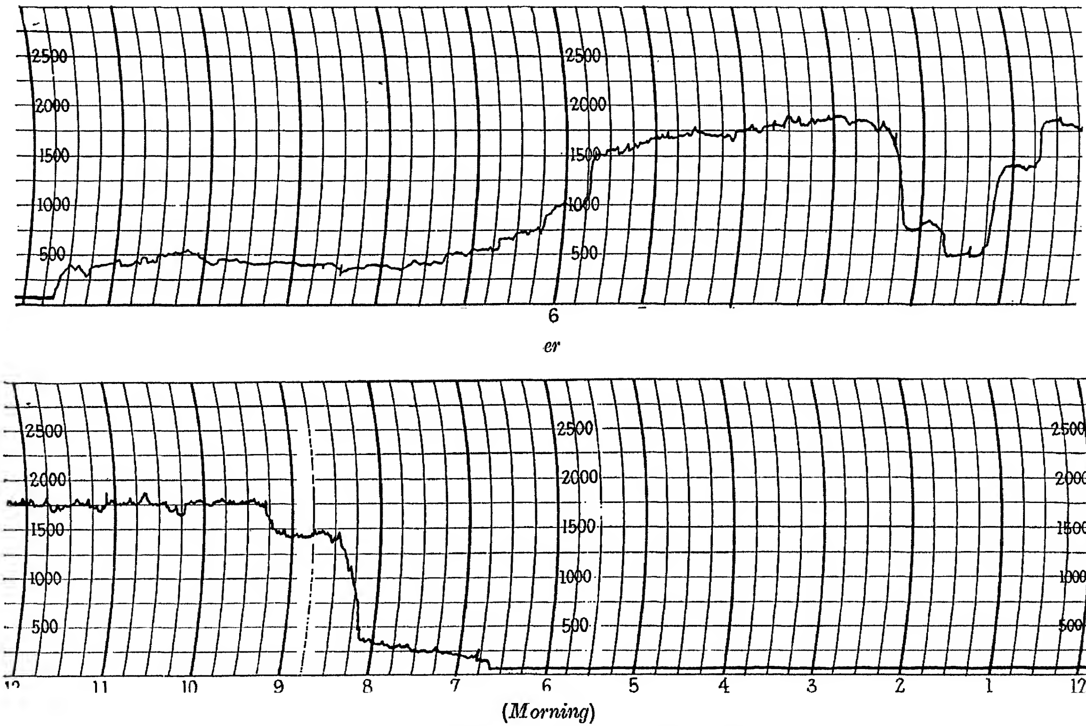

FIG. 17. AUTOMATIC ROTARY LOAD CHART

The staff organization and details of records kept in connection with automatic sub-stations is fully dealt with in the portion of this section dealing with automatic sub-stations.

TRACTION SUPPLY

In connection with traction supply certain regulations have to be observed for testing and recording the leakage current, rail drop, and insulation resistance of the system.

Referring to Fig. 18, the regulations require that the current passing from the earth plates through the recording ammeter L.A. to the negative busbar must not exceed 2 amp. per mile of single track or 5 per cent of the total current output of the sub-station. Also, the earth connections must be maintained so that a pressure not exceeding 4 volts shall produce a current of at least 2 amp. from one earth plate to the other, indicated by the ammeter A1. This test must be made at least once a month.

The insulation resistance of all feeder cables must be tested once a month with a "megger," and should not be allowed to fall below 10 megohms per mile.

A continuous record must be kept of the difference of potential between the farthest point of the rail and the negative feeding point. If at any time the voltage drop exceeds 7 volts, indicated at the recording voltmeter R.P.V. in Fig. 18, immediate steps must be taken to reduce it below that limit.

These precautions are necessary, due to the fact that damage is done to the gas and water mains by electrolysis if stray earth currents are allowed to flow. It is necessary, therefore, that the resistance of the traction return conductor should be as low as possible. If the system is a large one, in addition to bonding the rail joints, negative feeders have to be run to different

points of the track, and in some cases negative boosters are used.

There is also another question to be considered, that is, the difference of earth potential at the negative feeding points where two or more track feeders are used. If the feeders are of unequal length, or the traffic on one part of the system becomes heavier than the

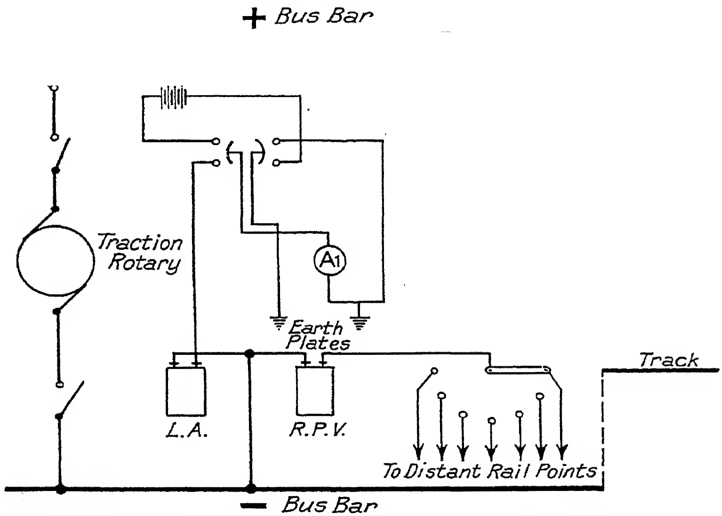

Fig. 18. Diagram of Connections for Tests of Earth Return, and Rail Point Drop on Traction Systems

traffic in another district fed by a different feeder, the voltage drop on one feeder will be greater, causing a difference in the earth potential at the feeding points. A gas main running near to such negative feeding points may carry current and have a potential + to the rail at one point and – to the rail at another point. The potential and polarity vary according to the load on the feeders. Thus current will enter and leave the gas

main at various places, and in time holes will be formed due to electrolytic action causing an escape of gas.

If the feeders are two or three-core cables it is possible to equalize the feeder drop by arranging to switch out one or two cores on the lightly loaded feeder to increase the resistance. To compensate for one feeder being longer than another on an evenly loaded system, a permanent resistance may be connected in the sub-station in circuit with the longer feeder. A more satisfactory way, which will cater for all conditions of load, is to arrange an automatic regulator to cut resistance in one feeder and out of another as required, controlled by pilot wires connected to the negative feeding points. Any difference of potential at these points will actuate a polarized relay which energizes a motor operating a sliding brush on a tapping switch connected to the resistance. The automatic switch need not be working continually, as it can be arranged for the sub-station attendant to put the gear in commission when the load demands, and when the differential voltmeter shows that the difference of earth potential at the feeding points is becoming too great. This voltage difference should not exceed $1\frac{1}{2}$ volts. The regulation governing this stipulates that if a galvanometer is connected at any place between the rail and any pipe in the vicinity, it shall always be able to reverse any current indicated by interposing a battery of three Léclanche cells connected in series if the direction of the current is from rail to pipe, or by interposing one Léclanche cell if the direction of the current is from pipe to rail.

Fig. 19 shows a regulator and resistance for such a purpose, which is sometimes called an anti-corrosion regulator. A diagram of connections for a regulator controlling two track feeders, together with pilot wires for metering, etc., is shown in Fig. 20. It will be noted

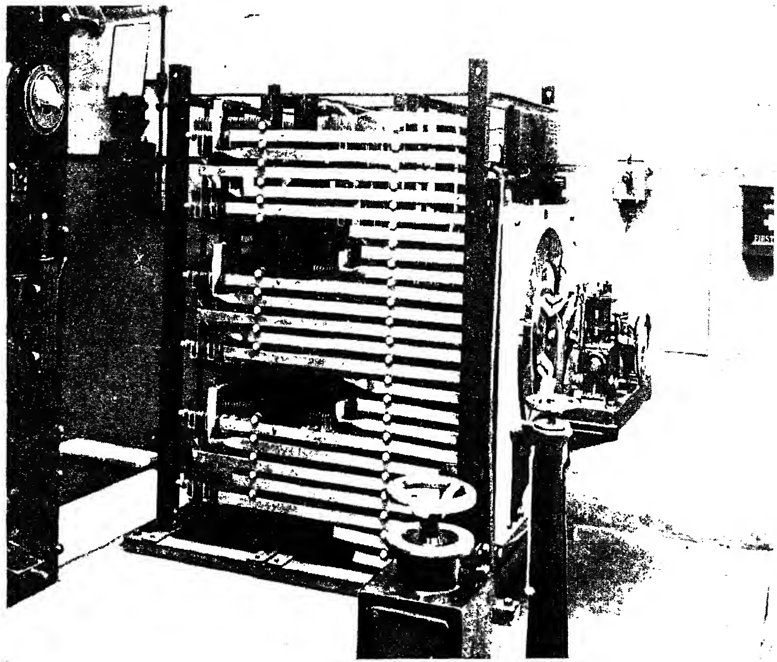

Fig. 19. Anti-corrosion Regulator

that the rail in this instance is earthed through a shunt to the water main. A continuous record of the leakage current through this shunt is recorded at the sub-station. The recording voltmeter is connected through pilots as shown in the diagram. No. 2 feeder has three cores, so that regulation may be obtained by opening the switches controlling one or two cores by hand. This can be done by the attendant when the load conditions do not warrant the regulator being in service, or may be used in addition to the regulator for obtaining extra resistance when the conditions are abnormal.

It will be noted that three pilot wires are run between the sub-station and each feeding point, and by an arrangement of change-over switches these are made to operate the regulator and also instruments recording the following: volts between gas main and track, difference of potential between the track feeding points, rail drop, and earth return current. The arrangement is as follows: leakage ammeter (L.A.) is provided with a two-way double-pole switch *E* to enable readings to be taken on either No. 1 section or No. 2 section of the track. A tumbler switch is provided for use when the instrument is not working. Gas main to track voltmeter (G.T.) is provided with a two-way double-pole switch *F*, and as the same pilot wires are also used for the leakage ammeter, two two-way switches are provided in each lead so that with switches *A*, *C*, *B*, and *D* over to the left, the leakage ammeter may be switched on to No. 1 or No. 2 section by the change-over switch *E* as required. With switches *A*, *C*, *B*, and *D* over to the right, the gas main to track voltmeter can be connected to either section through the change-over switch *F*.

The differential voltmeter (Diff.) is connected through a tumbler switch direct to the track feeding points, the same pilots being used for the polarized

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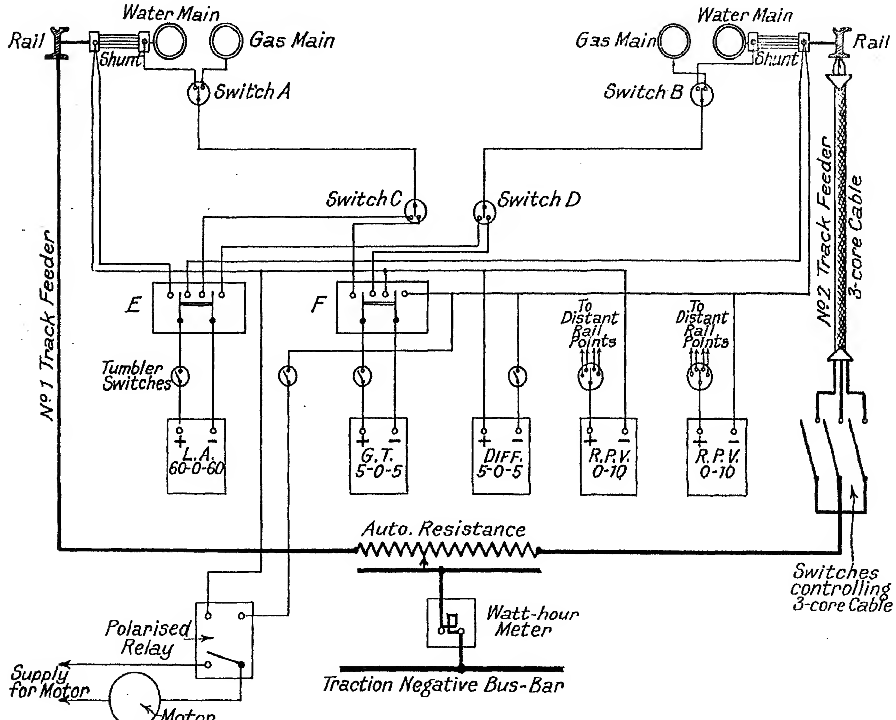


FIG. 20. DIAGRAM OF CONNECTIONS FOR ANTI-CORROSION REGULATOR WITH NEGATIVE PILOTS

relay in connection with the anti-corrosion regulator, and also for the negative leads of the two-rail point voltmeters.

With this arrangement trouble due to electrolysis is reduced to a minimum, and a complete record of the necessary data is kept.

TRACTION OVERHEAD LINE TESTS

Leakage on the overhead trolley wires must be tested weekly in order that cracked insulators may be detected and replaced before a breakdown occurs. For this purpose a sensitive ammeter A2 is inserted in each feeder, when all cars are in during the night and there is no load on the line. If signal lamps or any lighting is connected, care must be taken to have them switched off before the leakage test is taken. A leakage test ammeter usually has two scales reading 0–5·0 and 0–0·05 amp., one terminal being connected to the positive busbar through a resistance, switch, and fuse, the other terminal being connected to each feeder in turn through a multi-way switch. When the feeder circuit breaker is open, the sensitive ammeter is inserted in the line by putting the multi-way switch on the contact connected to the feeder to be tested, and then completing the circuit by closing the ammeter switch. A diagram of connections is shown in Fig. 21.

The reading should first be taken on the high scale of the ammeter A2, and then if no reading is observed the low scale should be used. The maximum reading should not exceed 1/100 part of an ampere per mile of track. If it should be found that the leakage exceeds $\frac{1}{2}$ ampere per mile of track indicated at the sensitive ammeter A2 in Fig. 21, the leak must be localized and removed within 24 hours.

It is necessary to have a resistance in circuit to limit the current to a safe value in case a car should come

on the section during the test, or a repair gang working on the track start up a motor for rail grinding, etc. If no resistance were inserted, under these conditions the ammeter would probably be burnt out before the fuse cleared.

An alarm bell switch should be fitted to every traction feeder circuit breaker to give an alarm when

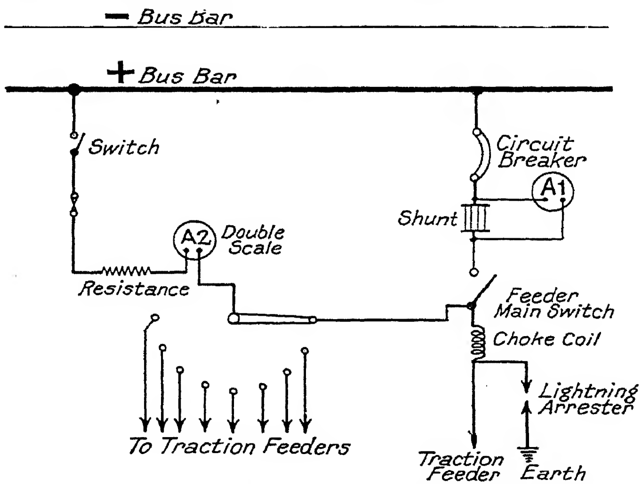


FIG. 21. DIAGRAM OF CONNECTIONS FOR TRACTION FEEDER LEAKAGE TEST

the breaker opens. The alarm bell should be tested every night by the attendant opening each circuit breaker in turn to see if the bell rings, and attention should be given to any bell switch that fails to ring the bell. Usually it is found that any trouble in this direction is due to a dirty contact.

DIRECT CURRENT SWITCHGEAR

The cleaning of direct current switches and circuit breakers is of the utmost importance (and this will be

emphasized more in the automatic sub-station details), as most heating trouble can be entirely removed by cleaning the contacts.

The use of a millivolt meter gives a very good indication as to the state of the contacts of a switch or circuit breaker. The method is to join the millivolt meter to a pair of flexible leads terminating in sharp points having insulated handles. The drop across the switch whilst carrying current can then be measured by connecting the pointed terminals across the switch contacts.

For testing busbar joints and connections the drop should be taken across the joint, and should not greatly exceed the drop of an equivalent length of the bar.

Contacts that are dirty should have the dirt removed by a clean rag and the switch or circuit breaker should be worked in and out a number of times to remove any oxidation of the copper. A little vaseline applied to the contacts will help to make a good contact. On no account should emery paper or carborundum be used unless the contacts are badly pitted, in which case the contacts will have to be ground in until contact is made evenly over the whole surface.

The millivolt drop across the contacts of a circuit breaker in good condition should not exceed 10 mV, but better results than this can be obtained. Table No. III shows the millivolt drop on some large circuit breakers before and after cleaning. A little vaseline was smeared on the contacts when the breakers were cleaned. No. 1, a 5000 amp. breaker, had a drop of 100 mV before cleaning, which was reduced to 10 mV after cleaning. No. 2, which was already in good condition, was reduced still further to 6 mV after cleaning. All the breakers were of the laminated brush type.

The overload trips of direct current breakers should occasionally be tested. If a machine breaker is to be

tested, this can be done actually on load by wedging some part of the mechanism so that the breaker cannot trip and increasing the load on the machine until the magnet or plunger attempts to operate. This practice is not to be recommended, however, as a fault may occur when the breaker is wedged in, or the breaker may be accidentally tripped out on load when interfering with the mechanism. Where low-voltage auxiliary machines are available, such as feeder boosters or battery boosters, such machines can be used for testing, generally by connecting only one temporary lead to the apparatus to be tested, the busbar being used as the return lead. The usual station ammeters in circuit can then be used to read the current and no special test instruments are required. A diagram of this arrangement is shown in Fig. 22. Of course, two leads will be required where the busbar cannot be used, such as testing a traction feeder circuit breaker by a lighting feeder booster. In this case the lighting feeder booster leads must be entirely disconnected before the test leads to the traction feeder breaker are connected up.

TABLE III

Showing Millivolt Drop across Circuit Breaker Contacts Before and After Cleaning

No. of C.B.	Capacity of C.B. Amperes	Load on C.B. During Tests Amperes	Millivolt Drop	
			Before Cleaning	After Cleaning
1	5000	4000	100 mV	10 mV
2	5000	4200	10 mV	6 mV
3	4000	3000	34 mV	10 mV
4	5000	4500	45 mV	11 mV
5	5000	4000	17 mV	8 mV

Reverse current circuit breakers should be tested this way wherever possible, and never by reversing the machine. This is a dangerous practice especially on interpole and compound rotaries, as the shunt field has to be weakened to such an extent that the field produced by the series turns builds up in the opposite direction with such rapidity that the machine will flash over. Serious damage has been done on more than one occasion to both the machine and switchgear when the relay has failed to operate during a test carried out in this manner.

CARE OF MACHINES

Rotary convertors, motor convertors, motor generators, boosters, and all electrical machines in a substation should be regularly blown out with an air compressor to remove the dirt from the windings and the accumulation of fluff and metal dust from behind the commutator risers. If the armatures are not blown out frequently the dirt will become so firmly established that no amount of blowing will dislodge it, and if a flash-over occurs the dirt will catch fire and possibly ruin the armature. The dirt, once having caught fire, will continue to smoulder for a long time after the machine has been shut down, for it is difficult to use a fire extinguisher with any effect, as the seat of the fire cannot be reached.

COMMUTATORS

A commutator that has a fine burnished surface should not be cleaned with an abrasive material, but just wiped with a clean dry rag. If the commutator is cold the rag may be damped with a little paraffin, but this should afterwards be cleaned off with a dry rag. When a machine is running excited the rag should never be held in the hand. A stick should be kept for

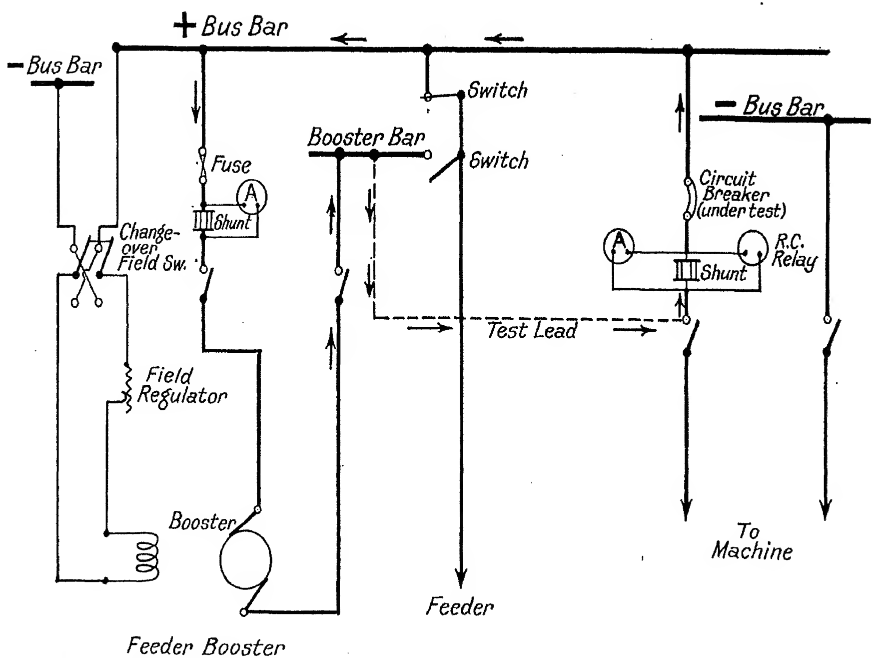


FIG. 22. DIAGRAM OF CONNECTIONS FOR TESTING CIRCUIT BREAKER USING FEEDER BOOSTER

this purpose with a rag fastened to one end. Severe burns have been caused to attendants' hands by machines flashing over at the moment when the commutators were being wiped over. The condition of a commutator depends to a certain extent on the grade of brush used. A hard carbon brush usually wears the commutator less than a softer type of graphitic brush, which contains a certain amount of abrasive material in its composition. Electrographitic brushes are now being extensively used on commutators with very good results. These brushes are mechanically harder than the soft graphitic types, but cause less wear of the commutator.

As a rule, a grade of brush that causes little commutator wear requires renewing more frequently than a brush that wears the commutator more. It is better, however, to spend a little more on brush renewals and save the inconvenience and expense of putting the machine out of commission for commutator grinding.

SPARKING AT DIRECT CURRENT BRUSHES

Sparking may be the result of one or more of the causes enumerated below—

Loose connections at the brush terminals and elsewhere on the machine.

Imperfect bedding of brushes.

Incorrect brush pressure.

Brushes sticking in holders.

Brushes vibrating in holders.

Flats and low bars on the commutator.

Projecting mica.

Brush holders too far from commutator causing vibration.

Incorrect position of the brush rocker.

Unequal spacing of brush arms.

Open circuit or bad joint in armature.

Short circuit in armature.

Incorrect strength of commutating poles, etc.

The testing and treatment for some of these troubles are obvious, but some details with reference to others will be of interest.

High Mica. There is no doubt that it is beneficial to undercut the mica on commutators of most machines. It is very difficult to determine for certain if the mica is absolutely flush and is not projecting slightly above the surface of the segments. When recessing mica great care should be taken not to make the depth of the groove greater than the thickness of the mica, and the latter should be cleanly cut so as to leave a groove of rectangular section, as a V-shaped slot may have the extreme edges of the mica uncut, which will cause more trouble than if the mica had not been recessed at all, as the uncut edges are free to move in the slot.

No better or cheaper tool can be had for recessing mica than a short length of hacksaw blade held in a piece of tubing bent flat, a handle being attached to one end slightly bent up. The blade should project a little in front of the tubing in order that the operator can see to guide the blade along the mica. When the mica is recessed a smooth file should be used to slightly bevel the edges of the segments.

Brush Pressure. The correct pressure varies according to the type and size of brushes used, generally $1\frac{1}{2}$ lb. to 2 lb. per square inch will suffice. The manufacturer's advice with regard to this, however, should always be followed.

A small spring balance is very handy for testing the brush pressure, but care must be taken to see that the pull is central on the brush. It is no use hooking the balance on to one pigtail, as the brush will be forced to one side of the box and a false reading obtained. A thin piece of sheet steel bent at right angles, to pass

under the spring plunger or finger, with a small hole at the other end to take the hook of the balance, will ensure getting a straight pull, the true pressure being just when the spring is leaving the brush, for if the spring is lifted too far a false reading will be obtained. Some machine makers issue a table giving the exact length of spring which will give the desired pressure. When this is done it is a good practice to cut a small cardboard template to the exact length required and adjust the spring tension to this template. The brushes on the bottom brush arms should have a little extra pressure to compensate for the weight of the brush. It is important for all brushes to have even pressure, as the distribution of the load is governed by the contact drop, and the brushes with the heavy pressure take an undue share of the load with the result that these brushes are apt to glow and the flexibles burn out. If too little pressure is applied sparking will take place, as the brushes are not making good contact, due to slight unevenness of the commutator.

Flats and Low Bars on the Commutator. Low bars on a commutator are usually due to the commutator segments being loose. When this occurs the commutator should be tightened up after a long run on load when the commutator is warm.

Flats are often due to bad connections between the armature winding and the commutator, also to high mica, and should be removed in the early stages with a commutator stone. The cause of the trouble, however, should be looked for by examining the commutator risers for bad soldered joints or test for the bad joints in the following way, if facilities are at hand—

Pass direct current at low voltage—usually from 2 to 5 per cent of the normal terminal voltage—through the armature when at rest, and measure with a low reading voltmeter the difference of potential between

adjacent segments round the commutator. A bad joint or open circuit will be indicated by a relatively high reading compared to the remainder. Current for this test can be obtained from a battery or an auxiliary booster. If a low-voltage alternating current is available, a telephone receiver may be substituted for the voltmeter, in which case the fault is indicated by a loud hum in the receiver. The same test may be used for detecting short circuits in the armature. In this case, however, the faulty connection will be indicated by an abnormally low reading on the voltmeter, or if a telephone receiver is used by a correspondingly faint hum.

Incorrect Position of the Brush Rocker. This is frequently a cause of sparking, and should be corrected by finding the neutral position as follows—

Remove all the brushes from their holders except one positive and one negative, and trim these brushes so that they do not span more than one segment. Then connect a low reading voltmeter across the brushes. With the armature at rest excite the field from an auxiliary source, such as a battery at about a quarter normal pressure or even less, the field current being suddenly switched on and off. An E.M.F. will be induced in the armature winding. There will be no deflection on the voltmeter, however, when the brushes are in the neutral position. The test should be repeated with several positions of the armature, and the mean of the neutrals so found should be taken. Instead of switching the field on and off the switch may be closed and the field rheostat moved rapidly backwards and forwards. This, of course, cannot be done with a multi-turn rheostat. This test is known as the kick test, and gives the neutral point at no-load. Another method of finding the neutral position is to remove a brush and fit in its place a piece of wood of the same size, in which two pieces of carbon rod have been fixed with pointed

ends spaced about one segment thickness apart. Connect the carbon rods to a low reading voltmeter and run the machine fully excited. Move the rocker backwards and forwards. The neutral position is the one in which the voltmeter gives zero deflection.

Incorrect Strength of Commutating Poles. Commutating poles should be adjusted so that their strength is correct at full load, for sparking will occur if the

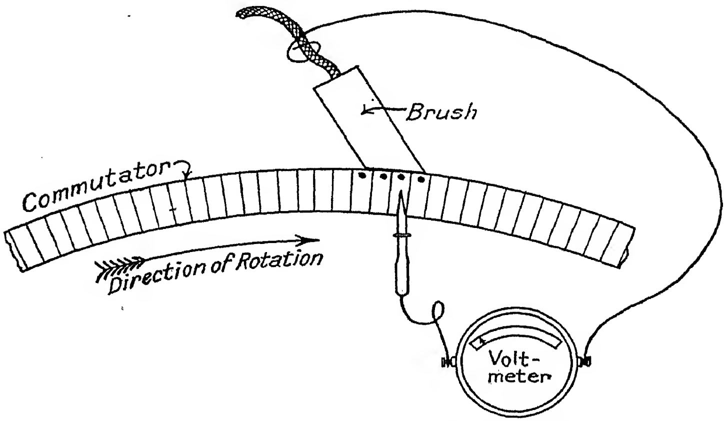


FIG. 23. SHOWING METHOD OF TAKING BRUSH POTENTIAL CURVES

commutating poles are too strong or too weak. Usually the commutating poles are so bolted to a machine that they may be packed out from the yoke with soft iron packing if the poles are too weak and a non-magnetic packing, such as brass, if the poles are too strong. Another method to weaken the commutating poles is to connect a diverter, consisting of German silver strips, across the windings to shunt some of the current.

To adjust the commutating poles to the correct strength brush potential curves should be taken as follows—

The machine is run at full load and the voltage is measured between the brush and several equi-spaced points on the commutator directly under the brush, as illustrated in Fig. 23, where four points are shown. The two outside points must be near the edges. It is as well to mark four dots on the outside brush on the arm which is being tested, and touch the commutator with the pointed terminal directly under each dot.

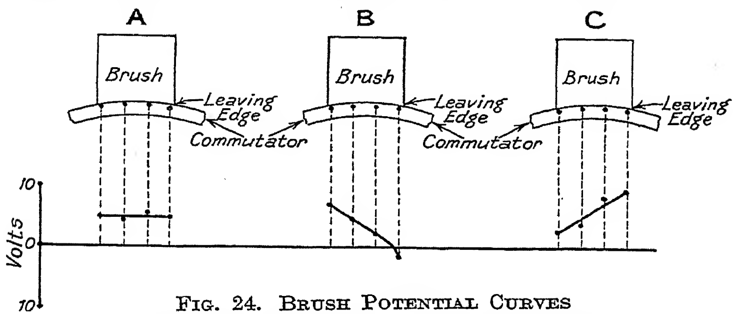


FIG. 24. BRUSH POTENTIAL CURVES
A—Straight line commutation *B*—Over commutation
C—Under commutation

Fig. 24 shows three curves, *A* illustrating straight line commutation, *B* over-commutation (commutating poles too strong), and *C* under-commutation (commutating poles too weak). The commutating poles should be adjusted to get a result corresponding to curve *A*. The curve, however, should droop a little towards the leaving edge, as this has been found to give the best practical results.

Unequal Spacing of Brush Arms. The spacing of brush arms can be checked by carefully measuring with a steel tape or wrapping a stout piece of paper round the commutator (a recorder chart is useful for this purpose), marking the leaving edge of the brushes on each arm and then measuring to see that the spaces are all equal. If the spaces are found to be unequal the

brush arms or spindles must be carefully adjusted. There is usually enough play in the bolt holes holding the arms to the rocker for this purpose. The difference in the spaces should not exceed one-sixteenth of an inch, and even less on smaller machines.

Slip-ring Brushes. Slip-ring brushes on rotary convertors, especially machines of large size, sometimes give trouble by the flexibles blackening or burning, which may be due to the brushes running at too high a current density, although theoretically the density may be correct. It is very difficult in practice to get the brushes to share the load equally in large heavy current machines, and unless ample margin is given the brushes taking the greater current will heat up and damage the flexibles. Usually a different grade of brush fitted to the machine will cure the trouble, but sometimes an improvement can be made by slotting the brushes across the face by making two or three saw cuts, so as to make a perfect bedding at a number of points, thus making the contact drop on each brush equal.

It is often found that the brushes that have been treated in this way continue to run better even when worn down past the slots, as the even bedding is maintained. Where lubricating-brushes that are sometimes fitted to slip-rings give trouble by under-lubricating, or over-lubricating, and getting too much oil on the slip-rings which is liable to get on the armature and collect dirt, the expedient may be tried of fitting one or two soft graphitic self-lubricating brushes per ring. The number required for any particular machine can be tried by experiment. The author has found that one lubricating to every three brushes usually gives very good results for medium speed machines.

Flash-over. When a flash-over occurs on a machine it may be necessary to get the machine on load again

without delay if there is no spare plant available. Sometimes after a flash-over, which is usually on a traction machine, the commutator and brush gear appear badly damaged, but in reality the damage may be slight. The following precautions, however, should be taken before starting up the machine. An inspection of the armature should be made to ascertain if there is any smouldering dirt behind the commutator, which would be likely to burst into flame when fanned by the windage of the armature when starting up.

The insulation resistance of the machine should be taken if a "megger" is available. If no megger is at hand a quick test may be made by using the paralleling voltmeter. It is usual for the paralleling voltmeter to be connected across the positive switch and, if this is the case, by closing the positive circuit breaker only, a circuit will be made from the positive busbar through the voltmeter to the postive terminal of the machine. If there is an earth on the machine the circuit will be completed through earth to the negative busbar, which will be indicated on the voltmeter. In this way a reliable test is quickly made by just closing the circuit breaker. The earth connection to the machine frame should be examined to see that it has not been burned through due to the flash-over, as if this has occurred the test will be unreliable. The machine may now be run up and the commutator wiped over. If the commutator is badly blistered, however, the rough parts must be levelled down with a smooth file. Usually, however, it is only the edge of the commutator that suffers badly, in which case the end brushes may be taken out if it is essential that the machine should be got on load quickly. When the machine is excited care should be taken to see that the polarity is correct, as this may become reversed on a compound wound machine. If a field switch is provided for separately exciting the

shunt field from the busbars, the polarity can easily be corrected. Where there is no switch connected for separate excitation temporary leads may have to be run, in which case extreme care must be taken not to break the field circuit without a discharge resistance unless at low pressure, as the circuit is highly inductive. Where another machine is running in the same sub-station, it is often possible to correct the polarity of a machine that has been reversed simply by closing the negative and equalizer switches when the machine is standing. When this is done the series compound winding of the standing machine shunts the compound winding of the running machine, the current being in the right direction to magnetize the poles with correct polarity. The greater the load on the running machine the more effective this is. A machine that has been put on load in a hurry after a shut-down due to a flash-over should, of course, be shut down as soon as the load conditions will allow and receive proper attention.

MERCURY-ARC RECTIFIER SUB-STATIONS

Introduction. The mercury-arc rectifier is manufactured in two distinct types, the steel cylinder and the glass bulb.

With the latter type, mercury-arc rectifier sub-stations for public supply are a comparatively recent innovation, for engineers-in-charge of supply undertakings were very loath to trust their reputation to plant having for its most vital part a piece of apparatus made of glass. However, one or two very large public supply undertakings have tried out this type of plant and found it not only very satisfactory in operation and reliable in service, but in one instance at least it was the only possible economical solution to a particularly pressing problem.

Mercury-arc rectifier plant of 800 kW capacity can

be housed in a building 30 ft. × 20 ft., which includes accommodation for four transformers with the necessary E.H.T. switchgear and also the low-tension switchboards. Thus these small stations of quite a useful capacity can be erected on sites situated in close proximity to the heaviest loaded section of the direct current network, fed from perhaps a somewhat distant rotary convertor sub-station. Such sub-stations may be designed to feed into the three-wire network or to boost across the outers only. In some cases it is better to combine the two methods in the one sub-station.

The rectifier also finds a use in boosting the voltage at the extreme end of a long traction system, especially where a track is extended and the cost of running a new feeder out from the rotary convertor sub-station would be prohibitive.

Like the transformer, the rectifier is a piece of static apparatus, simple in construction and operation, efficient, particularly the higher voltage types, and yet does not require constant attendance.

These sub-stations may be erected in units so that the growth of the sub-station is in direct proportion to the increase in load demand and sub-stations of 2000 kW capacity are giving very satisfactory service.

Rectifiers may be designed for operation on supplies of any voltage or number of phases or even periodicity.

In the examples given in this section of the book it will be noticed that there is no highly complicated sequence of operations, no multiplicity of expensive and delicate relays, and no abundance of protective relays for the control equipment itself. The reader will, no doubt, be surprised at what appears to be an almost total lack of protective devices as compared with the number of relays to be found when other types of converting plant are in operation, but the supposed deficiency is more apparent than real.

Automatic Rectifiers. It is not the intention of the author to treat in this section with the design of the mercury-arc rectifier unit, but rather to deal with the construction, operation, and the maintenance of a complete sub-station.

For a full description of the theory of the mercury-arc rectifier, the reader is referred to a separate section of this work.

The general principles of this type of sub-station are fairly well known now and understood, but a general resumé will be given here in order that a better understanding of that which is to follow may be obtained.

The essential parts of the glass-bulb type of rectifier are the main step-down transformer and the evacuated glass-bulb containing the mercury. The bulb may have three or six main anode arms, according as the impressed current is three- or six-phase. The mercury pool forms the cathode terminal. The main anodes are connected to the free ends of the star-connected secondary winding of the main step-down transformer, whilst the neutral point forms the negative terminal.

In order to start up the rectifier it is necessary to create a certain minimum mercury vapour pressure within the bulb to form a conducting path for the main current from the anode arms to the cathode. This is accomplished by fitting auxiliary carbon electrodes and an ignition electrode within the base of the bulb chamber to form an entirely separate single-phase rectifier, which produces sufficient vapour pressure to permit the main arc to strike up and be maintained.

Each rectifier unit is fitted with anode and cathode choke coils connected in the main alternating current and the direct current circuits respectively. The principal function of the anode choke coils is to enable adjustment to be made to the electrical conditions of the alternating current circuits in order that bulbs,

having widely differing characteristics, may be made to operate in parallel satisfactorily, and to share the load equally between them.

The cathode choke coil, however, helps to damp down the amplitude of the pulsations or ripples in the direct current circuit to a reasonable value, whilst at the same time causing the current waves from each alternate anode arm to overlap so that absolute zero is never reached, and the arc in consequence is more easily maintained at periods of very light or no loads.

The main and the auxiliary circuits are amply protected by suitable fuses, and as an additional protection an overload circuit breaker is fitted in the main direct current circuit.

Testing Plant. After a station has been erected and the plant is ready for testing, a thorough inspection is necessary to see that no tools, nuts, bolts, washers, etc., have inadvertently been left behind in places likely to result in damage being done when pressure is impressed upon the apparatus. Cabling and wiring connections should then be checked up and an occasional terminal tried for tightness here and there. All oil switch tanks should be lowered so that the contacts may be inspected and tested, and the following points carefully noted.

Firstly, test all connections for tightness, and see that all contact making surfaces are smooth, clean, flat, and rigid ; then test with the switch closed for good contact with feeler gauges. Should any contact permit the passing or the partial passing of a ·0015 in. feeler gauge, then that contact should receive further attention from the fitter. To test for good contact lightly smear an even thickness of some dark greasy substance upon the surface of the contact—just a slight film will be all that is necessary—then close the switch on to small sheets of very thin white paper, when upon opening the switch a clean and clear impression of the contacts will

be found to have been impressed upon the sheets of paper. This is a very good test, and immediately shows up a poor or bad fitting contact.

All sparking or auxiliary contacts should also be tested for contact making, and it should be particularly noticed that these contacts make before, and break after, the main contacts. This is very important, as otherwise the main contacts will become damaged during service and the effect will be cumulative until ultimately the main contacts may be utterly destroyed.

All contacts should be tested with a megger between all phases and from each contact to earth, in order that any fault which may exist may be found, if possible, before a pressure test is made.

For viewing contacts in inaccessible positions, a small hand mirror and a flash lamp are of great value.

The next series of tests should be of a mechanical nature, all moving parts being tried for smoothness of action, all catches tried for sureness of hold, and all guides for correctness of alignment. Vibration should not jar a switch out of position, and tests should be made to see that a reasonable amount of jolting and hammering in close proximity has no ill effect.

The pressure test should next be made on all E.H.T. circuits, such as busbars, transformers, switchgear, and the cabling connected to these individual parts.

Pressure tests should have a value of twice the declared normal working pressure plus 1000 volts for one minute, as recommended by the B.E.S.A., so that plant to work under a normal stress of 11,000 volts requires pressure testing at 23,000 volts.

When performing these tests it is very important indeed to fence off the gear and the leads, so that men still working in the station on some other plant may not wander into the danger zone.

A typical diagram of connections for pressure testing

the primary winding of a delta-connected transformer is given in Fig. 25, and is self-explanatory.

When testing an induction regulator of the type

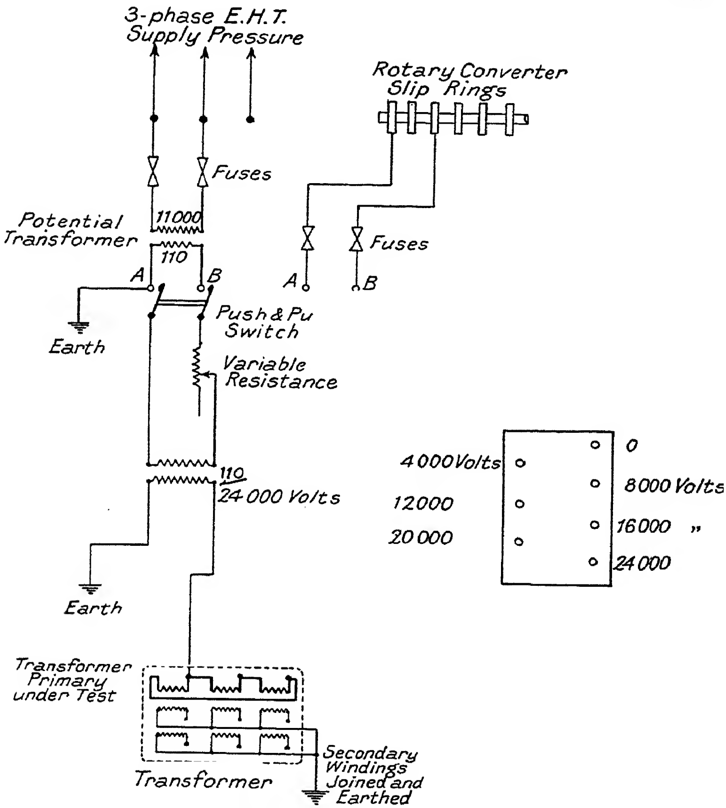


FIG. 25. PRESSURE TESTING A TRANSFORMER

shown in Fig. 26, a slightly different method is adopted to save time. The transformer primary winding is disconnected at *A*. *B*. and *C*. and the ends of the cable

left well clear of earth, so that the induction regulator is now divided up into three entirely separate single-phase circuits. To pressure test each phase separately to earth, and then to test between each phase, would take a considerable amount of time besides being unnecessary. The quicker and better way is to join terminals *A* and *B* together by means of a piece of wire and then to earth the third phase *C*. Pressure should then be applied to the terminal *A*, which will test both *A* and *B* phases between *C* phase and earth. For the second test join both *B* and *C* phases together and earth the third phase *A*. Apply the pressure to terminal *B* and then phases *B* and *C* are tested between phase *A* and earth. This then completes the whole of the pressure test in two operations, instead of the six that would be necessary if this method were not adopted.

Busbars may be tested in the same way quite easily.

One test only is necessary on the transformer, since it is delta-connected on the primary side, and for this test the reader is referred to Fig. 25.

All pressure tests are now completed.

Overload trip coils next require testing, but this has already been treated in the paragraph, " E.H.T. Consumers' Sub-station," to which the reader is referred.

All doors to the E.H.T. plant may now be locked up, after which the busbars may be charged from the ring main or E.H.T. feeder supplying the sub-station.

Set all transformer overload coils at some safe value, say 150 per cent and the inverse time lag fitting to operate at, say, six seconds.

The transformer switches are then ready for closing after the low tension plant has been tested.

All metal-clad parts, such as switchgear chambers, transformer tanks, etc., should be efficiently earthed

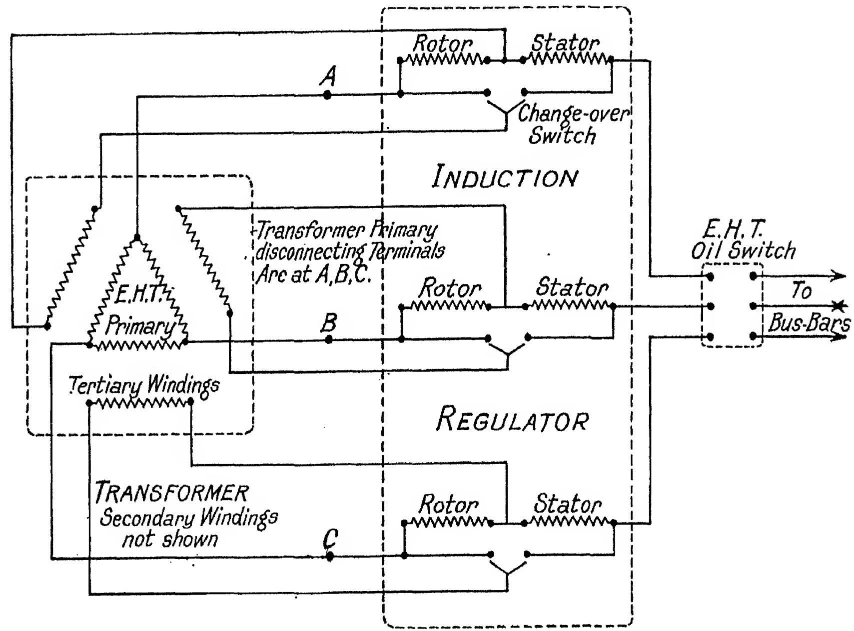


FIG. 26. METHOD OF PRESSURE TESTING AN INDUCTION REGULATOR

and sweated joints made where the earth strips join the main station earth cable.

Further tests can only be mentioned in a general manner, each sub-station requiring individual attention and consideration, therefore the matter will be left at this point, because certain of the original testing is continued at intervals during maintenance.

However, set the overload coils on the direct current circuit breakers to trip at some safe value dependent upon the size of the bulb, or whether the circuit breaker is fitted to a rectifier or to a feeder.

All fuses should be inspected for contact and correctness of value to protect the circuit to be controlled.

Test all low-tension circuits with a megger, including the secondary winding of the main step-down transformer.

The sets should now be ready for starting up, so the transformer oil switch may be closed, the rectifier alternating current switch, direct current circuit breaker, and lastly the direct current switch.

Immediately the alternating current switch was closed the bulbs should have attempted to strike up. However, that particular function will receive attention in the two following paragraphs.

Bulb Excitation Circuit. The function of the bulb exciting circuit is to maintain the cathode at an electron emitting temperature on very light loads. The circuit forms a complete single-phase rectifier within the bulb, and commences to operate automatically immediately the main alternating current switch is closed on the rectifier.

Referring to Fig. 27, the exciting anodes $AE1$ and $AE3$ are connected through choke coils to a separate winding on the three-phase regulating auto-transformer, whilst the cathode of the bulb is joined to the middle point of the winding.

The normal voltages at the terminals on open circuit should be—

$AE1$ to $AE3$	120 volts
$AE1$ to $AE2$	60 volts
$AE3$ to $AE2$	60 volts

and when the bulb strikes up in a normal manner, the approximate voltages may be—

$AE1$ to $AE3$	55 volts
$AE1$ to $AE2$	35 volts
$AE3$ to $AE2$	35 volts

With normal operation the voltage drop in each of the exciter choke coils, that is, from $F1$ to $S1$ and from $F3$ to $S3$, is approximately 50 volts. These voltages are dependent upon the amount of current passing through the circuit and are, therefore, approximate only, but between $AE1$ to $E2$ and between $AE3$ to $E2$ the pressure should be the same, so also should the voltage drop across each of the choke coils be equal.

The normal current passing through the circuit depends upon the type of bulb, and should conform to the following table of values—

Size of Bulb	D.C. Exciter Current
250 amp.	6 to 7 amp.
150 to 200 amp.	$5\frac{1}{2}$ to 6 amp.
40 to 100 amp.	5 to $5\frac{1}{2}$ amp.
20 to 30 amp.	4 to $4\frac{1}{2}$ amp.

The current adjustment may be made by varying the amount of packing in the magnetic circuit of the choke coils. An increase in the packing results in less

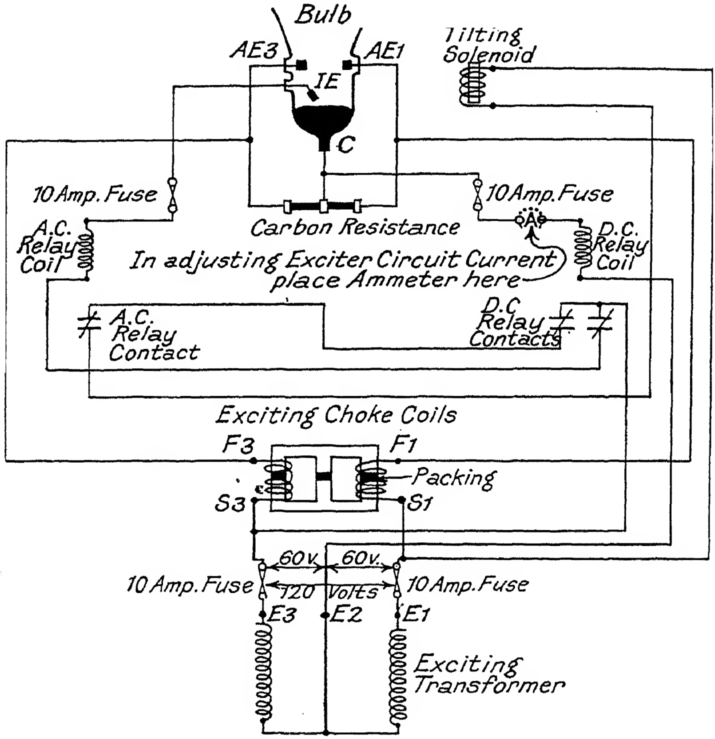


FIG. 27. DIAGRAM OF TILTING, STARTING, AND EXCITER CIRCUITS FOR MERCURY-ARC RECTIFIER

choking action and more current, whilst, conversely, less packing gives proportionately lower current values.

It is sometimes found that the requisite amount of current cannot be obtained in that way, so one only

of the choke coil connections should be reversed, e.g. change $E1$ from $S1$ to $F1$ and $AE1$ from $F1$ to $S1$. This will usually cure the defect, and adjustment can then be corrected in the usual way.

After each adjustment the choke coil clamps should be made quite a tight fit, as otherwise an inaccurate reading may be given by the ammeter, and also excessive vibration and hum may be set up.

A further adjustment of the current value may be necessary after the first 100 hours of service, due to the increase of the internal resistance of the bulb.

As the life of the bulb increases, a periodic check should be made and the current kept up to its maximum allowable value for the type of bulb, as otherwise the bulb will keep dropping out probably on light loads, causing heavy kicks in voltage, objectionable flickers, and lastly, a shortening of the life of the bulb due to the continual tilting operation taking place in an endeavour to keep the bulb alive.

If after the adjustment of the current the bulb still drops out, then it can be somewhat reconditioned by placing it in a spare set and running for a period of two or three weeks on exciter current only, after which treatment the bulb will be fit for a further period of useful service.

The diagram of connections given in Fig. 27 shows the circuit and the relays for complete automatic operation of the mercury-arc rectifier bulb.

STRIKING UP THE BULB

In order to start up the bulb, it is necessary to bring the ignition electrode IE into contact with the mercury cathode pool C, and this is arranged by mounting the bulb in a cradle free to oscillate about a fixed fulcrum. This action may take place by hand, or may be made entirely automatic in its operation. In the latter case

IE is made alive before and during the tilting operation, but is cut out of service immediately the bulb has struck up. In the case of hand tilting *IE* is energized during the tilting action by closing a push-button switch, or it may be in circuit through a carbon shunter contactor which is made to break the circuit upon the bulb igniting. *IE* is connected through a resistance in the hand tilting types, or a relay coil in the automatic types to terminal *E*3 of the exciter winding, and after contact is made between the ignition electrode *IE* and the mercury cathode pool *C*, the bulb returns by gravity to the vertical position. This breaks the circuit between *IE* and the mercury pool *C*, and an arc is drawn out between them which ionizes the mercury vapour in the bulb, and thereby enables the exciting electrodes to function.

If the bulb is cold, the tilting operation may have to be repeated a number of times before sufficient vapour pressure is produced to enable the exciting electrodes to pass current through the circuit. If the vacuum in the bulb is normal, that is, about ·045 mm. of mercury pressure corresponding to a mean temperature of 70° C., and if the exciter current has been correctly adjusted, the bulb will strike up with a bluish-white light.

The operating voltages of the exciter circuit can then be checked up, and should approximate to those values already given.

Should the vacuum within the bulb be poor, the mercury will form a heavy mirror on the walls of the bulb immediately an attempt is made to strike up, and the mercury will also assume a dirty appearance. In this event the bulb is not fit for service and should be replaced by a new one. If, however, the mirror effect is only slight, the bulb should be left to operate on the exciter circuit only for a few hours, by which

time its condition will have become normal providing there is no break in the glass, or no faulty seals round the electrode caps.

If the arc is drawn out between the ignition electrode *IE* and the mercury cathode pool *C* upon tilting the bulb, but after repeated efforts the bulb fails to strike up, then the vacuum is defective ; that is, assuming that the correct voltages are obtained at the exciter electrode terminals. This may be confirmed by noting the sound emitted from within the bulb upon tilting by hand, for if the mercury falls back into the base of the chamber softly instead of emitting a sharp metallic click, then the vacuum is certainly poor and a new bulb should be installed.

All bulbs gradually blacken in service, but this does not indicate any defect ; it does, however, reduce the quantity of mercury in the cathode pool, so that it may be necessary to make a slight adjustment to the cradle carrying the bulb, to ensure a definite contact being made between *IE* and the mercury cathode pool *C* during the tilting action.

By studying the diagram of connections given in Fig. 27, the sequence of operations for automatic starting-up may easily be followed from the description now to be given.

Firstly, the exciter winding is charged up immediately pressure is impressed upon the main regulating auto-transformer. The circuit is then made from *E*3 through *FE*3 to the two contacts on the direct current relay. From one of these contacts a lead is taken to the alternating current relay coil, thence through a 10 amp fuse to *IE*, whilst from the other contact a lead is taken to a contact on the alternating current relay, thence to the tilting relay operating solenoid, and so through another 10 amp. fuse to *EI*. This operation energizes the tilting relay solenoid, causing it by the

action of the magnetic rocker to tilt the bulb cradle, while at the same time the alternating current relay coil and the ignition electrode *IE* are energized, causing the contacts of the alternating current relay to open to de-energize the tilting relay, and so inaugurate an oscillatory motion to the bulb cradle. If all is normal, the ignition arc is drawn out and current will then flow via the mercury vapour within the bulb from *E*3 through the exciter choke coils to the cathode pool *C*, through the direct current relay coil to the middle point of the exciter winding at *E*2. This will then energize the direct current relay coil, which will open its contacts to cut off the supply to the alternating current relay coil and also the tilting relay solenoid.

The reason for failure of any one operation should now be a comparatively easy matter for the reader to trace out and correct.

FAN RELAYS AND THEIR FUNCTION

In the main cathode lead between the cathode of the bulb and the cathode choke coil is inserted a relay of the maximum current type, i.e. a relay which has for its coil a thick copper tape of ample section through which the whole of the current from the bulb must pass on its way to the main sub-station busbars. The relay is fitted with a soft iron plunger carrying a set of contacts, that are made when the current through the relay has reached a predetermined value, which is usually about 40 amp. for all bulbs of 100 amp. capacity or more, and drops off again when the current has become somewhat less than that value.

The fan has a three-phase squirrel-cage type motor, fed from an entirely separate winding on each leg of the main regulating auto-transformer, and has a working voltage of 50.

The blades of the fan are made either of sheet

steel or wood ; the latter, however, gives the better result.

In Fig. 28 are shown the characteristics of a 40 to 100 amp.-type of bulb, that is, a bulb with a capacity of 40 amp. without any artificial cooling apparatus, and 100 amp. if cooled off by an air blast from a fan. It will be seen that the voltage drop in the case without

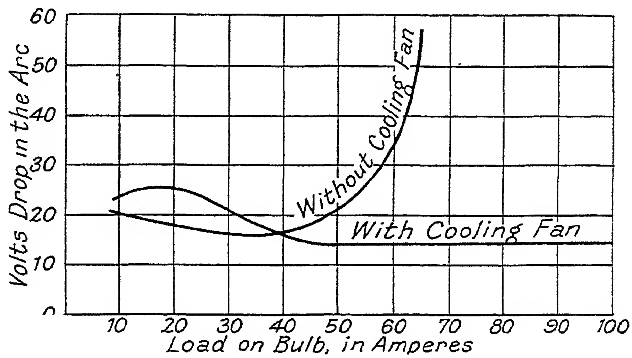


FIG. 28. CHARACTERISTICS OF 40 TO 100 AMPERE-TYPE MERCURY-ARC GLASS BULB

a fan is extremely rapid as the load increases, because the temperature of the bulb is permitted to rise unchecked very quickly. When the bulb is cooled by artificial means it is possible, as will be seen, to reach a load density of 100 amp. with a subsequent very steady drop in voltage in the arc over a large range of load. The constant drop of 15 volts is a measure of the work done at the cathode in vaporizing the mercury and in the production of ions for the maintenance of the arc.

Obviously, then, the fan is a very important piece of auxiliary apparatus, for if it failed to function for any length of time on peak load, the bulb would "flash

over," i.e. cease to function as a one-way valve and give a reversal of flow of current sufficient probably to damage the bulb.

"Flash-overs," however, do not always damage the bulb, as the fuses in the main anode circuit blow and put the set out of service for the time being until it receives attention.

After a "flash-over" the bulb will sometimes strike up in a normal manner, but perhaps with an unusual pink tinge of colour in the arc. If, however, the bulb is left working on exciter current for half an hour or more, the bulb will probably have assumed a normal colour and be ready for taking up the load once more.

The extreme simplicity of the auxiliary cooling apparatus tends to efficiency and reliability in operation, so that failures are very rare indeed.

It is important to see, when testing, that the fan rotates in the correct direction so that air is blown on to the bulb. If, on starting up, the fan is found to be rotating in the wrong direction, so that the air is being blown downwards, then by changing over two of the leads at the motor terminals correct rotation will be obtained.

COOLING LARGE AUTOMATIC RECTIFIER SUB-STATIONS

The efficient ventilation of a large mercury-arc rectifier sub-station is an important factor. The heat generated comes mainly from the main transformers and to a smaller degree from the bulbs and the choke coils.

One method of ventilation is the provision of louvres of ample size spaced at intervals around the walls of the sub-station, with the addition of cowls fitted into the roof.

Another method is to place the sets against one wall

of the sub-station and to fit a louvre into the wall with a suitable air filter, so that air may be drawn in by the fan from outside the building. An outlet is provided by the fitting of cowls into the roof.

The ideal method of ventilation is to run a chase beneath the sets which should be totally enclosed, with outlets taken through the roof. Thus the rectifier fans would draw air along the chase from outside the building through an air filter, and an additional extractor fan could be fitted in the outlet chamber. Thus a strong blast of air would be continually circulating through the sets.

In winter it may not always be necessary to run the extractor fan.

The main transformers could be housed outside and be of the outdoor type.

A RECENT TYPE OF AUTOMATIC MERCURY-ARC RECTIFIER SUB-STATION

The station about to be described was designed to boost up the low pressure at the extreme end of a feeder network in a residential area fed from a somewhat distant rotary-convertor sub-station. The plant consists of two 92 kW, three-wire self-balancing units, together with a remotely controlled bank of four units having a total capacity of 276 kW, which was connected across the two outer wires of the network.

Each 92 kW unit has two 200 amp., six-arm type bulbs giving 230 volts connected in series across the three-wire supply network. The voltage regulation is entirely automatic and balances the voltage across both sides of the network. The mid-wire or neutral wire is earthed through a resistance in the usual way, at the rotary-convertor sub-station.

The six-arm bulbs are housed in separate cubicles

apart from the control gear, and are cooled by air being drawn through suitable filters from outside the building by a single wooden bladed squirrel-cage motor operated fan, as previously described. These two sets run continuously on the busbars, which maintain a constant pressure at a predetermined value of voltage on the network.

The 276 kW bank consists of four 150 amp., three-arm type bulbs working in parallel and remotely controlled from a manually-operated rotary-convertor sub-station some two miles distant. It can be started up and shut down by the attendant-in-charge as load conditions require.

Since this station is in a residential area, there is a peak load at early morning, mid-day, and again in the evening at times varying with the time of the year and the weather conditions, so that the 276 kW bank is only switched in at those periods of peak loading.

The main sub-station connections are given in Fig. 29, and are self-explanatory.

The bank is controlled by means of a three-core, 7/20 rubber insulated lead-covered pilot cable. One core is used for controlling the starting up and shutting down of the 276 kW bank, while the other two cores are used for indicating the load of either the balancing units or of the booster bank, if the latter is in service. The complete diagram of connections is given in Fig. 30, and the method of control is now to be described.

STARTING UP

The attendant at the remote sub-station, upon finding the load on the 92 kW units to be about 90 per cent of their full-load capacity, closes *S* connecting the negative busbar through the pilot cable to the automatic mercury-arc rectifier sub-station. The action of

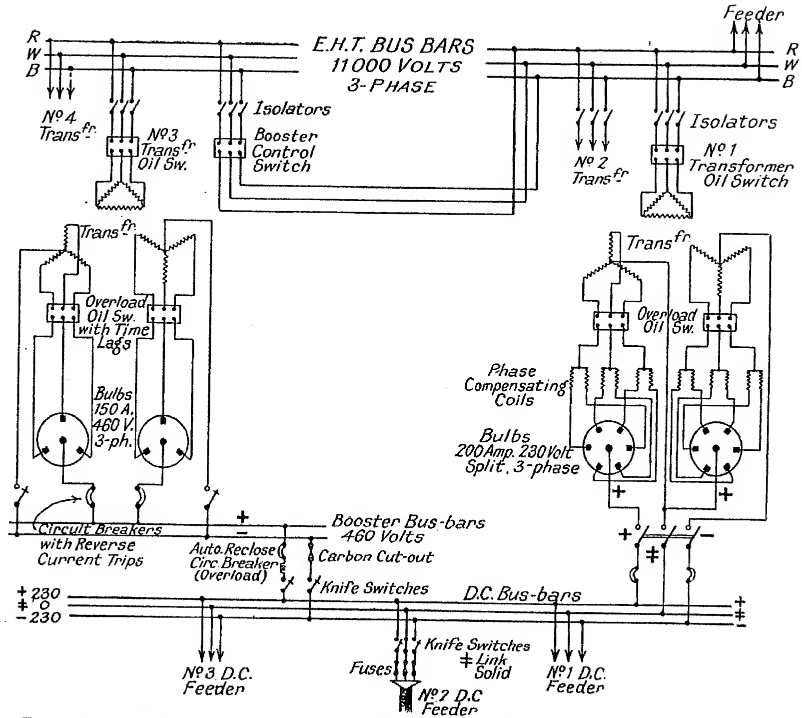


FIG. 29. DIAGRAM OF MAIN CONNECTIONS OF AUTOMATIC MERCURY-ARC RECTIFIER SUB-STATION (Example 1)

closing the 10 amp. switch *S* energizes the pilot relay *I* through a resistance providing the single-pole change-over switch is in the " Remote " position, which is the normal one. The energizing of *I* causes the relay armature to make contact at 1 *A*, thus energizing the oil switch closing contactor 2 through an auxiliary switch 2*B* on the booster control oil switch 4, which is normally closed when 4 is open. The contacts 2 *A* are then caused to close, which energizes the oil-switch closing solenoid 3, and thus allows the booster control oil switch 4 to close. This then charges the E.H.T. booster transformer busbars.

Since the transformer switches are normally left in the closed position, the transformers are immediately charged when 4 is closed. It is also arranged that in normal circumstances each rectifier unit of the bank has its alternating current and direct current switches and also the circuit breaker closed, so that upon 4 closing the rectifier bulbs will strike up by means of the automatic relays described in detail elsewhere in this section. When 4 has closed contacts 2*B* are opened to de-energize the contactor coil 2 and contacts 5*B* and 8*B* are closed to prepare subsequent circuits. When the arc in any one bulb is maintained, the excitation relay 7 of that particular unit, closes its contacts so that the first bulb to strike up will permit the solenoid relay 6 to close contacts 6 *A*, and so energize 9 the controlling coil of the automatic reclosing circuit breaker 10. This circuit breaker is entirely self-contained, and its function is to parallel the booster bank to the main direct current busbars on the positive side.

The negative side of the bank is connected to the direct current busbars through a fused carbon cut-out 14 and a knife-switch, both of which are permanently closed under normal circumstances.

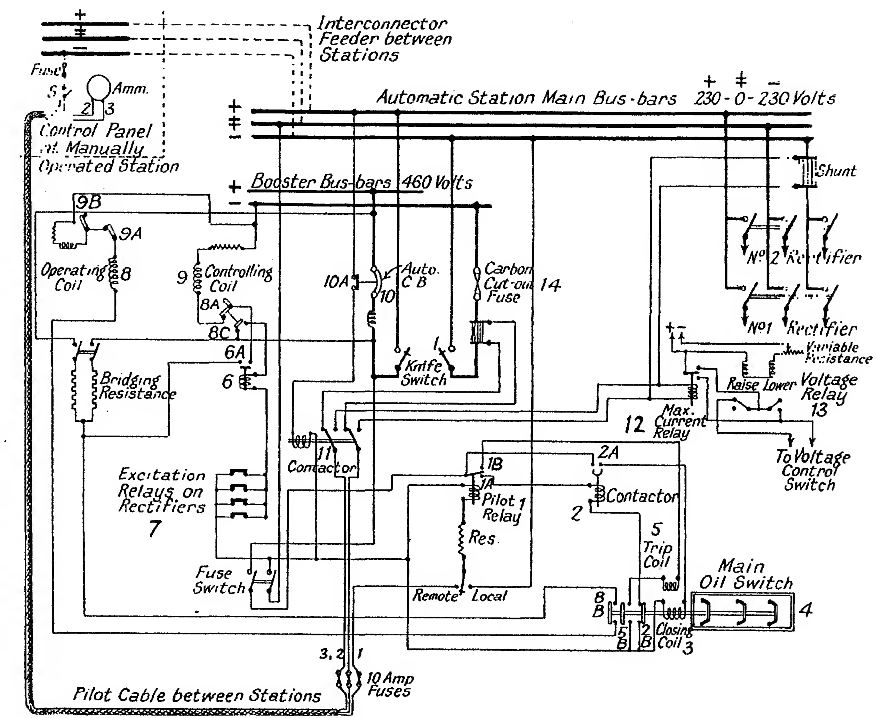


FIG. 30. DIAGRAM OF CONNECTIONS OF AUTOMATIC MERCURY-ARC RECTIFIER SUB-STATION

AUTO-RECLUSE CIRCUIT BREAKER 10

The controlling coil 9 closes contacts 9 *A* immediately it is energized and short circuits the resistance 9*B*, which causes the operating coil 8 to become energized, and so permits the closing of the automatic reclosing circuit breaker 10. After 10 is closed the contacts 8 *A* and 8*C* are broken to de-energize 9 and the relay 6 respectively. The operating coil is also interlocked with contacts 8*B* on the booster control oil-switch 4. Another contact 10 *A* on the auto-reclose circuit breaker closes with the closing of the breaker, and connects the ammeter at the remote controlling sub-station to the booster bank shunt. Thus the attendant-in-charge can read the load on the booster bank.

The auto-reclose circuit breaker 10 is set to operate on overload, and recloses again automatically after an adjustable time interval has elapsed, provided the overload condition has been removed.

Relay 12 is of the maximum current type operating at a predetermined value, that is, within the safe carrying capacity of the bulbs. If this safe value is exceeded then the function of the relay is to cut out of service the automatic voltage regulating relay 13, whilst at the same time it closes a contact to lower the voltage of the sets. If the overload condition still persists after the voltage regulator has reached its lower limit, then the rectifier overload circuit breakers will operate and trip, so that the sets will then be disconnected from the direct current busbars.

SHUTTING DOWN

When the load on the sub-station falls to within the capacity of the balancing sets, the booster bank may be shut down from the remote controlling sub-station by simply opening the small switch *S*.

The opening of this switch then de-energizes *I*, which enables the relay armatures under the influence of a light spring to make contact at *IB*, which energizes the booster control oil-switch trip coil 5 and so causes 4 to drop out. The opening of 4 opens contacts 8*B* and then 10 automatically breaks circuit. The booster bank is now disconnected from the direct current busbars and also the E.H.T. busbars, while all the circuits are prepared for starting up again when required.

From the time the small switch *S* is closed at the remote controlling sub-station until the 276 kW booster bank is feeding into the direct current network is approximately three seconds, whilst the shutting down operation is almost simultaneous with the opening of *S*.

VOLTAGE REGULATION

A voltage relay *I* in Fig. 31 is connected across the direct current terminals of the rectifier, and closes either of a pair of contacts at predetermined maximum and minimum values of voltage set to any required degree of closeness. Closing either relay contacts energizes one of the two solenoids 2, which mechanically operates contacts fitted to a bar. Each bar or arm carries a set of four contacts 2 *A*, two of which control the supply to the small operating motor 3 and are closed when the solenoid is energized, while one short-circuits the armature of the motor when the solenoid is de-energized and the remaining one is connected to the double-pole switch D.P. on the booster voltage control panel.

The two solenoids 2 are mechanically interlocked so that only one can operate the contactor at a time. Each arm is fitted with an adjustable oil dash-pot type time lag 4, which prevents the operation of the motor

due to momentary fluctuations in the voltage. The operation of one solenoid causes the motor to rotate in one direction, whilst the other solenoid reverses the direction of rotation.

The motor shaft and the regulator operating shafts are directly coupled together by worm reduction gears and chain wheels with a coupling chain. When either solenoid has operated, the motor revolves until one complete revolution of the regulator shaft has been traversed, irrespective of whether the contact of the voltage relay *I* has broken or not. At the completion of one revolution of the regulator shaft the motor armature circuit is broken by a contact 6 on the shaft 5. Should the contacts of relay *I* still remain closed a further complete revolution will be made. The limit switch 7 also opens the motor circuit by de-energizing 2 when the regulator has reached either end of its travel, and so prevents overrunning. The motor feed is interlocked with the excitation relays 8 on each balancing rectifier unit, so that failure of any one bulb to strike up or a total failure of the E.H.T. supply opens the motor circuit. Two push button switches are fitted at *A* to permit the manual operation of the regulator, and interlock switches *B* are also provided in the excitation relay circuit to close the circuit on any one bulb or set of bulbs if they are not required in service, whilst allowing the remaining sets to regulate in a normal manner. The regulating main shafts for the 92 kW sets and those of the booster bank are entirely separate, and the method of control is the same for both motors. The double-pole switch D.P. is normally left closed so that the booster sets will regulate in step with the balancing sets. The effect on the network pressure of having fully automatic voltage regulation may be seen from the actual charts given in Fig. 32.

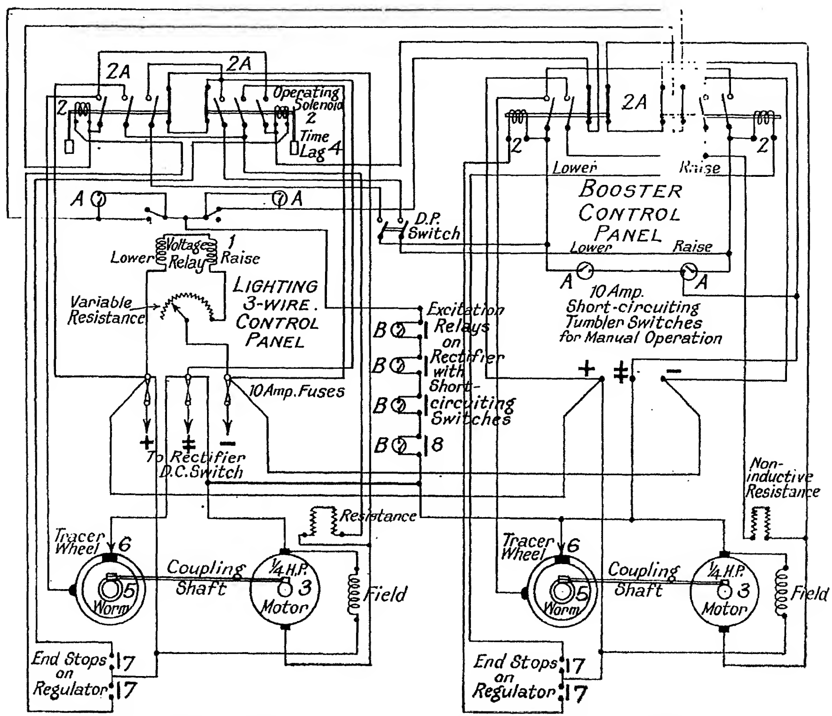


FIG. 31. DIAGRAM OF CONNECTIONS OF AUTOMATIC VOLTAGE REGULATOR

ANOTHER TYPE OF FULLY AUTOMATIC MERCURY-ARC RECTIFIER SUB-STATION

When it is found that a feeder from a sub-station has become so loaded that a heavy potential drop is experienced, then some kind of boosting arrangement becomes necessary.

To meet a case of this kind a sub-station was designed which would start up automatically when the voltage of the network fell to a predetermined minimum value. The sub-station consists of one 276 kW two-wire bank capable of self-controlling the voltage in a similar manner to that described in the previous example.

The main E.H.T. connections and the protective gear for this unit are exactly similar to those shown in the diagram for the first example. The supply to the two transformers is controlled by an electrically-operated oil switch provided with overload protection in each phase. The transformer switches are normally left in the closed position.

The direct current circuit breaker is the same type as described in the first example. The sequence diagram is given in Fig. 33 and operates in the following manner :

STARTING UP

Relay *I* is the master relay, being energized from a potential transformer on the E.H.T. supply, so that only under normal E.H.T. conditions will the station start up. This is obviously a simple form of protection in itself.

When the alternating current supply is normal the contacts 1 *A* are open, 2 is a voltage relay which cannot operate if 1 *A* contacts are closed, but under normal conditions its function is to allow contacts 2 *A* to open when the voltage across the direct current network falls

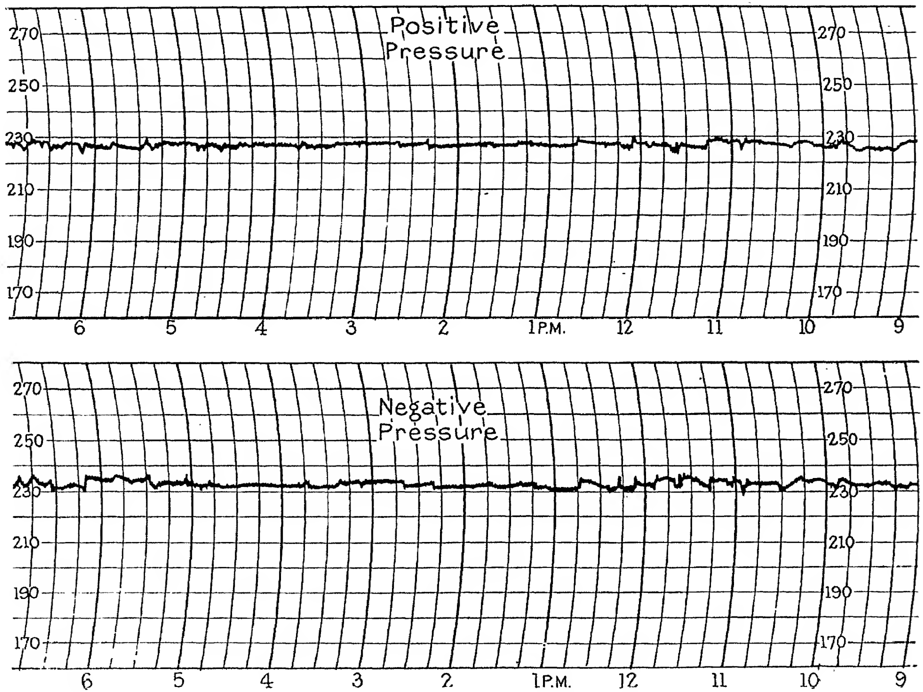


FIG. 32. VOLTAGE REGULATION CHARTS

to a predetermined value. Upon 2 *A* opening, 3 (a time delay relay) is de-energized through the insertion of a high resistance 3 *A* in the relay coil circuit. This enables contacts 3 *B* to close after a set time interval which is adjustable up to five minutes and so energizes 4, a contactor solenoid, causing the contacts 4 *A* to close, and in turn closes the main oil switch by energizing the closing solenoid 5. Six is an auxiliary switch which is closed when the oil switch closes and which short circuits 3 *A* to again energize 3. Contacts 3 *B* open now and 4 is de-energized to open the closing solenoid circuit. The transformers are now charged, the bulbs will strike up automatically, and contacts 7 close. There is a contact 7 for each bulb and these are connected in series. Any one may be shorted out by the tumbler switch if that particular bulb is not required in general service. Relay 8 is of the solenoid type which now becomes energized, and the contacts 8 *A* close to energize in turn 9, the controlling coil of the automatic reclosing circuit breaker. For the function and the operation of this circuit breaker return to the previous example.

The circuit breaker, having now closed, the voltage relay operates to adjust the rectifier voltage in a manner also explained in the previous example. Another relay 12, which is of the maximum current type, operates upon the full-load capacity of the bank being exceeded, and causes the voltage to be lowered until the overload condition has been removed.

If, however, the overload condition still persists after the voltage has reached its minimum value, the circuit breaker overload coil operates to disconnect the bank from the direct current busbars. After the overload condition has been removed the sets will again be paralleled with the network by the automatic reclosing of the circuit breaker on to the direct current busbars.

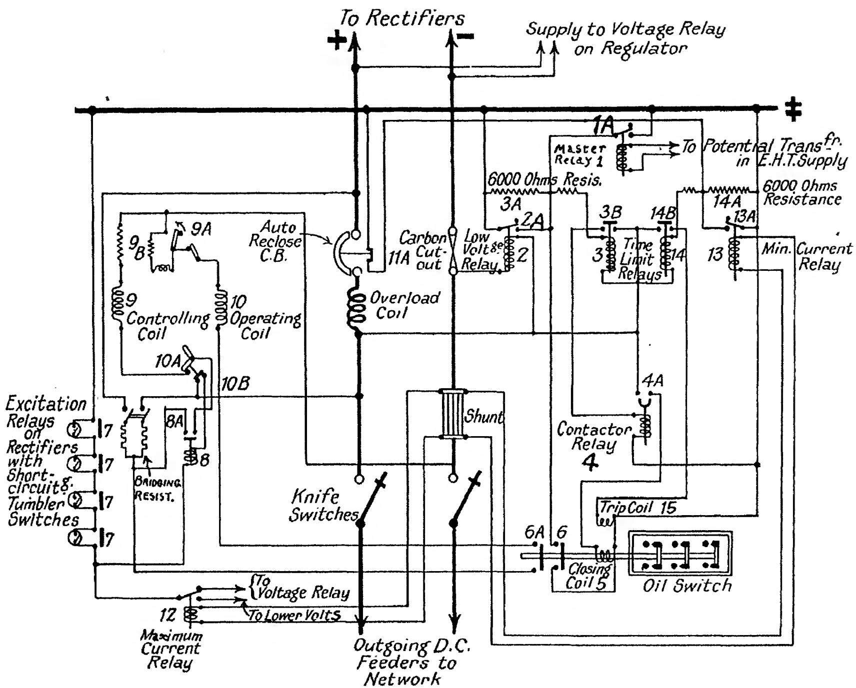


FIG. 33. DIAGRAM OF CONNECTIONS OF AUTOMATIC MERCURY-ARC RECTIFIER SUB-STATION (Example 2)

SHUTTING DOWN

When the load has fallen to a predetermined value, 13, a minimum current relay fed from a shunt in the feeder circuit opens contacts 13 *A* to de-energize the time delay relay 14 by inserting a high resistance 14 *A* in the coil circuit. After the time interval has elapsed contacts 14*B* close to energize the trip coil 15 to open the E.H.T. oil switch. The opening of the switch causes 6 *A* to open, which allows the direct current auto-reclose circuit breaker to drop out. An auxiliary switch 11 *A* on the direct current circuit breaker closes at the same time and resets 14 by short circuiting 14 *A*. The sets are now off the direct current busbars and all circuits are prepared for starting up quite automatically again as the load demands.

A typical actual voltage and load chart is given in Fig. 34 recorded at this particular sub-station, and gives a very clear idea of what can be achieved with a few simple inexpensive relays.

AUTOMATIC FEEDER CUTOUTS

In some cases an added protection for a small rectifier sub-station is necessary where it is working in parallel with an automatic rotary-convertor sub-station. In cases of a total failure of E.H.T. supply, the automatic rotary-convertor sub-station is usually locked out by a particular protective relay of one form or another dependent upon the make of the plant. Therefore, upon restoration of the E.H.T. supply, the rectifiers will automatically start up and feed into the direct current system usually within three seconds, and will endeavour to pick up the load usually taken by the rotary-convertor sub-station, with the obvious result of another shut down with possible damage to some of the rectifier plant if the protective apparatus should fail to function correctly.

To overcome such a possibility, a contactor may be used which opens the circuit of the inter-connector direct current feeder so that the rectifier sub-station will supply its own network only, and parallel itself again automatically only if and when the rotary

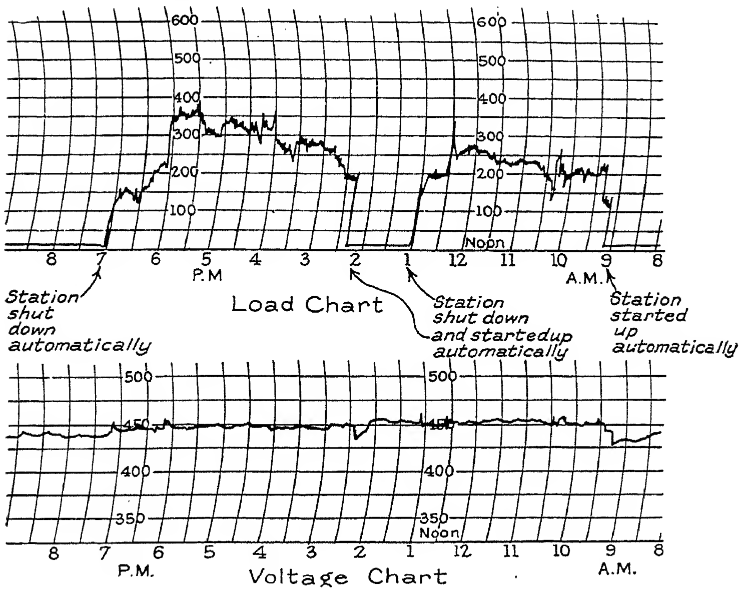


FIG. 34. VOLTAGE AND CURRENT CHART FOR AUTOMATIC RECTIFIER SUB-STATION IN EXAMPLE 2

Note 1. Drops in pressure at 9.15 a.m. and again at 2.25 p.m. bring in station on low voltage demand

Note 2. Observe automatic voltage regulation while station is running

convertor is feeding into its network at the correct voltage. One such contactor is given in Fig. 35, and it will be seen that the contactor closing coil is only energized from the inter-connector side, so that if the rotary sub-station shuts down the coil will be de-energized and the contactor will drop out to isolate

the rectifier sub-station from the rotary-convertor sub-station's network. As soon as the rotary convertor is feeding into the network again, the coil becomes once more energized and the contactor will close to parallel the networks.

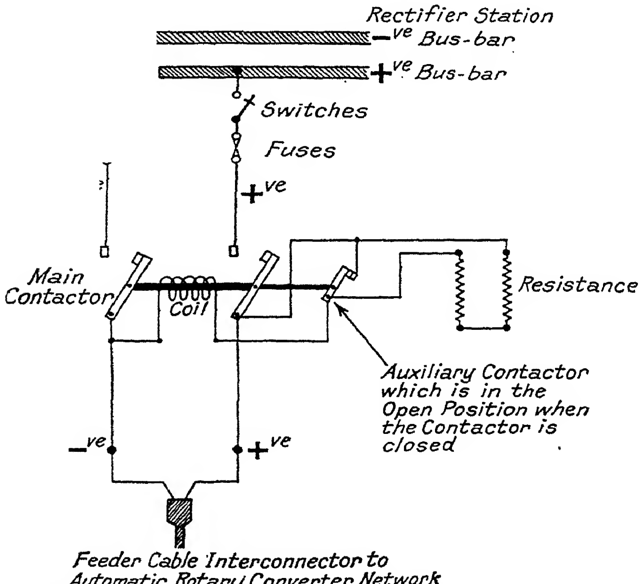


FIG. 35. DIAGRAM OF AUTOMATIC FEEDER CUT-OUT

MERCURY-ARC RECTIFIERS FOR TRACTION PURPOSES

Because of the new housing estates that have been constructed in the outlying districts of some of the large towns in this country, it has very often been found necessary to add one, two, or three half-mile sections to the tramcar track in order to give the inhabitants means of transport to and from their

places of business. The cost of running out the new feeders from the rotary-convertor sub-station would be almost prohibitive, but to run the new sections off the last existing feeder would produce such a heavy drop in voltage over the period of peak loads as to make such a scheme an impossible one. It is in such cases of that sort that the semi-automatic mercury-arc rectifier sub-station comes into its own and has the added advantage that it is cheap, efficient, reliable, and requires a minimum of maintenance attendance.

As a first equipment one unit of two 150 amp., six-arm bulbs working in parallel may be installed, further additional plant being installed as conditions necessitate. Such a unit is usually left running the whole time and maintains a constant voltage at the far end of the line. The connections to the overhead line and to the track are made immediately outside the sub-station, if only one feeder is found to be necessary.

The sub-station is semi-automatic in operation, each bulb having automatic reclose circuit breakers in the direct current circuit between the cathode of the bulb and the positive busbar, and also automatic reclose circuit breakers controlling the supply to the feeders.

The voltage can be regulated automatically if required by an induction regulator. The main step-down transformer can be of the outdoor type with a delta-connected primary winding and a twelve-phase secondary winding. The transformer is protected by three overload inversely time-lagged trip coils, one in each phase.

Where this type of plant operates from an E.H.T. supply of low frequency, choke coils are necessary in the negative circuit of the rectifier. The function of the choke coils is to damp down the amplitude of the ripple

until no interference is experienced in adjacent telephone lines. A diagram of connections of such a sub-station working from an E.H.T. supply of 25 cycles per second is given in Fig. 36.

When using mercury-arc sub-station plant of an automatic or semi-automatic nature for traction purposes, it must be remembered that the direct current circuit breaker controlling the supply to the feeder will open on overload and automatically reclose immediately, providing the overload condition has been removed. Should the overload be due to the overhead line being down, then immediately it is picked up by a track worker, the sub-station feeder circuit breaker controlling that line will reclose and the line will be made alive again.

Therefore it is necessary to warn all track workers, drivers, conductors, and others of this fact if an accident is to be avoided.

RESONANT SHUNTS

Where mercury-arc sub-stations fed from an E.H.T. system of low periodicity are used for supplying long lengths of traction line, considerable interference will be experienced on any telephone lines running parallel with and in close proximity to the track. It is therefore necessary to use some form of shunt for eliminating the inherent ripple in the traction line to obviate any disturbance on the telephone system.

This is especially so where the number of phases into which the feed to the bulbs is split up is a small number. The two traction units given in Figs. 36 and 37 illustrate this point, for in Fig. 36 the secondary current of the main transformer is split up into twelve phases, whereas in Fig. 37 only six are used, hence the difference in the treatment for the elimination of the ripple effect.

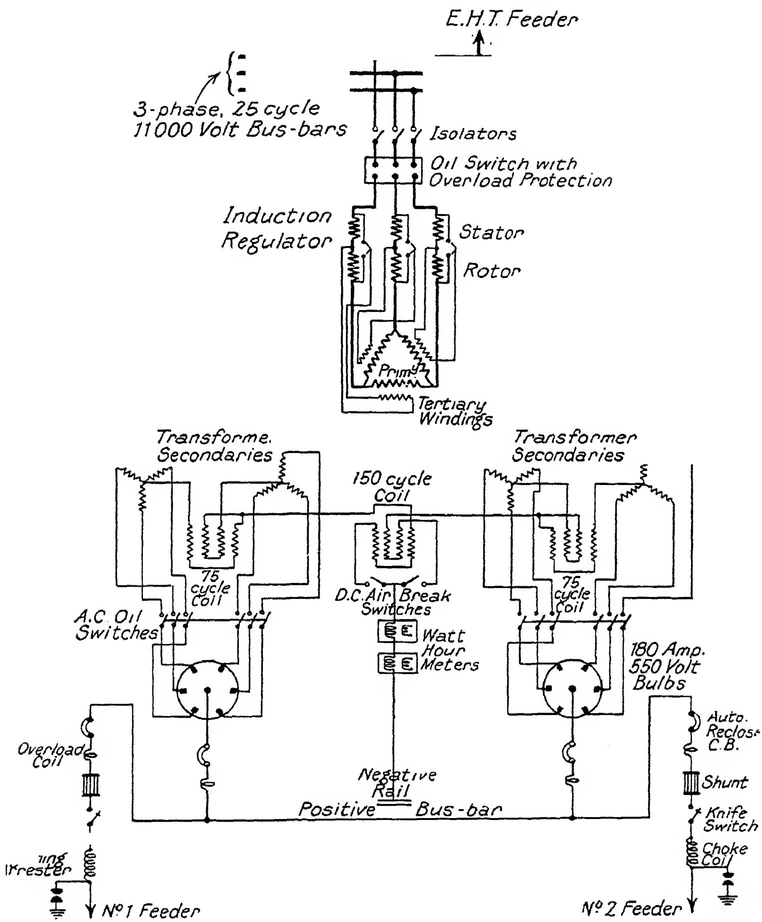


FIG. 36. DIAGRAM OF CONNECTIONS OF INDUCTION-REGULATED MERCURY-ARC TRACTION RECTIFIER SUB-STATION

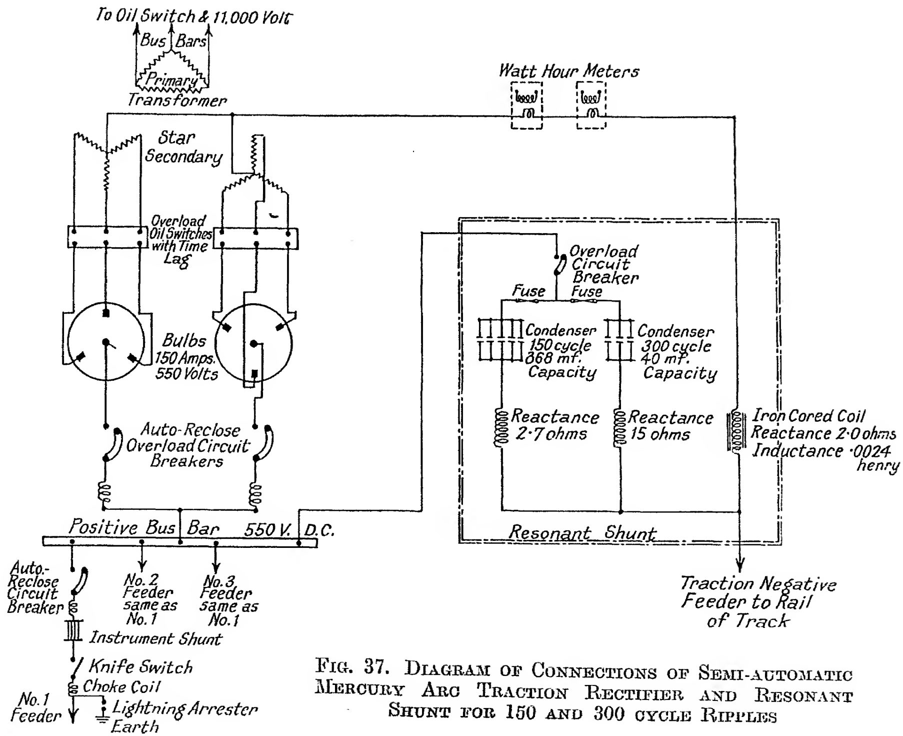


FIG. 37. DIAGRAM OF CONNECTIONS OF SEMI-AUTOMATIC MERCURY ARC TRACTION RECTIFIER AND RESONANT SHUNT FOR 150 AND 300 CYCLE RIPPLES

A piece of apparatus known as a resonant shunt will do all that is required, and a typical example will now be given.

Assuming the E.H.T. supply system has a periodicity of 25 cycles per second and the mercury-arc rectifier bulbs are of the three-phase, three-arm type, then there will be two predominant ripple frequencies of 150 and 300 cycles per second, impressed in the direct current circuit.

Therefore the resonant shunt must be designed to eliminate as far as possible these ripples.

To have the desired effect the resonant shunt must consist of a suitably designed iron-cored choke coil with an air gap, to be fitted into the negative feeder circuit between the rail track return and the transformer star-point. Also from the positive busbar two tuned circuits, one of 150 cycles per second and the other for a frequency of 300 cycles per second are required. The coils must be air-cored and the condensers should be built up in units and be oil-immersed.

The main wiring of the traction rectifier and the resonant shunt is given in Fig. 37, and suitable values of inductance and capacity are given for the tuned circuits. The choke coil and tuned circuits in this example will reduce the maximum value of the ripple to about 20 per cent of its original value, and should be approximately 10 volts if the mean value of the direct current circuit is assumed to be 550 volts. The maximum value of the ripple is, therefore, under 2 per cent of the mean value of 550 volts, and its effect could be ignored.

The illustrations now given are of typical mercury-arc rectifier sub-stations erected on sites chosen to suit the particular requirements of industrial, residential, and traction areas. Fig. 38 is the exterior of the sub-station given in Example 1, page 1405, and is in

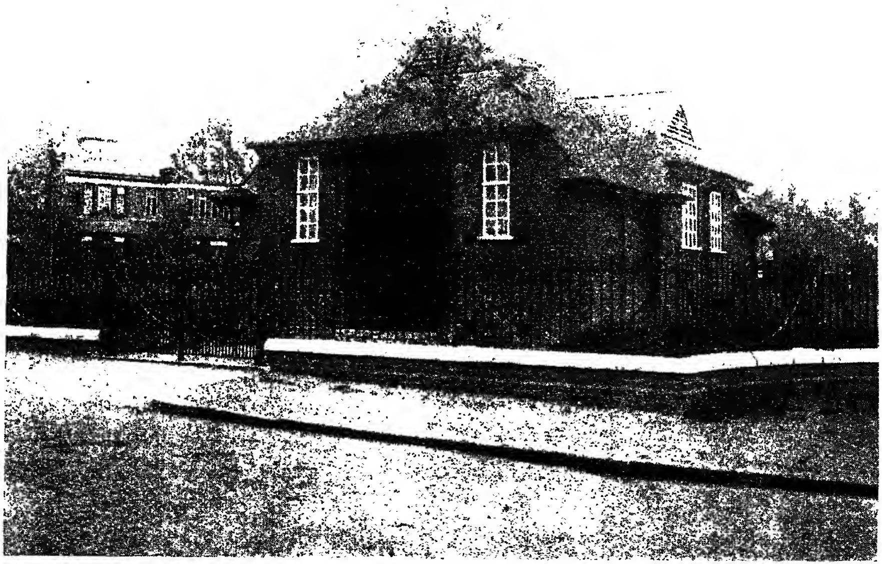


Fig. 38. View of Automatic Rectifier Sub-station Given as Example I

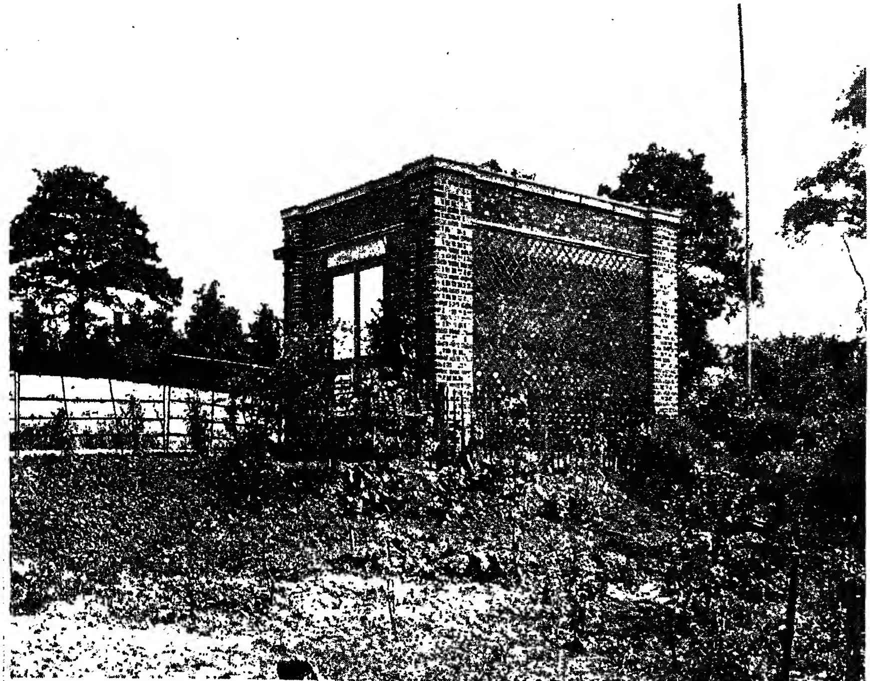


FIG. 39. VIEW OF MERCURY ARC RECTIFIER SUB-STATION OF 92 kW CAPACITY

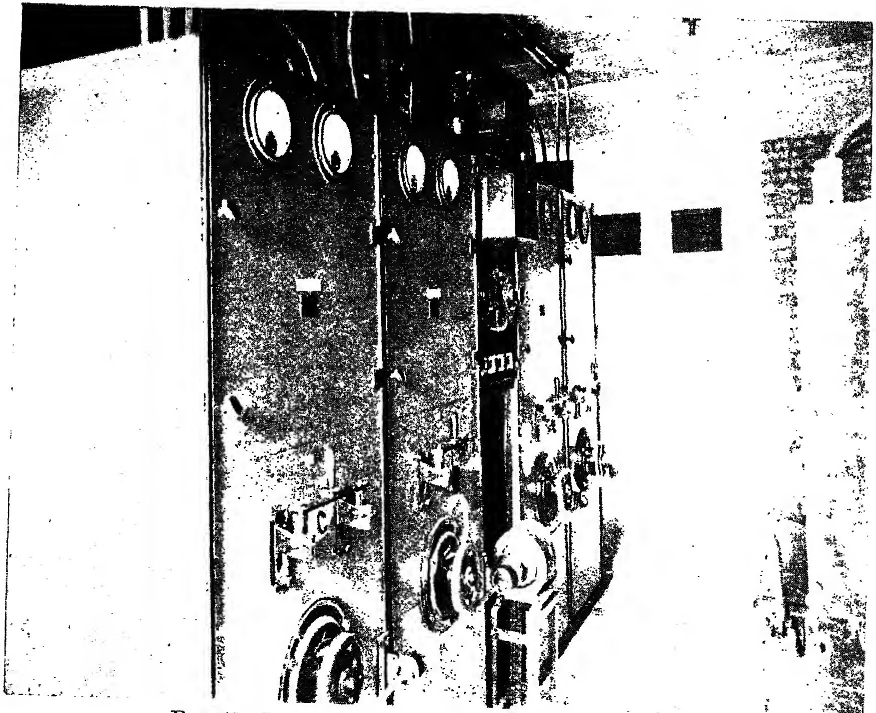


FIG. 40. INTERIOR OF SUB-STATION SHOWN IN FIG. 39

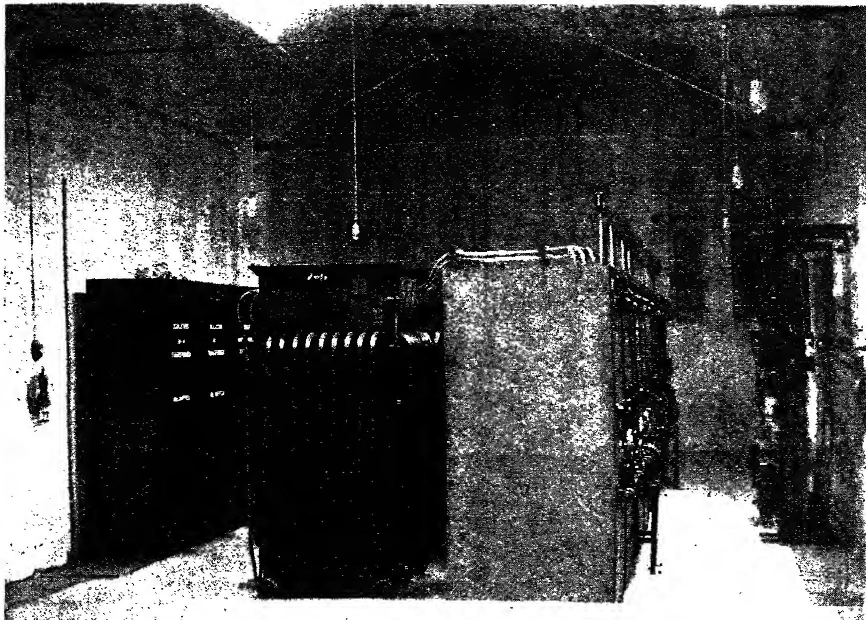


Fig. 41. Interior of Sub-station as Given in Example 2

keeping with the type of dwelling-house in that neighbourhood.

Fig. 39 is another type of sub-station situated in a district where the houses are built in the modern plain style.

Fig. 40 is an interior view of the sub-station shown in Fig. 39, and shows a bank of four 100 amp. type bulbs feeding into a three-wire network of 230 to 460 volts. The E.H.T. transformer switch is in the right foreground, and a good view is given of the automatic voltage control gear which is placed between the two pairs of rectifier units.

Fig. 41 is of great interest. This sub-station was built into an old mission hall or church which had fallen into disuse. It so happened that this particular site was the only one available in a dense industrial district which badly needed some form of pressure boost. The total capacity of the sub-station is 550 kW consisting of two banks of rectifiers, each comprising a set of four 150 amp. type bulbs feeding across the outers of a three-wire network at 460 volts.

The automatic control gear which is of the type described in the second example, page 1414, may be seen on the extreme right.

Fig. 42 illustrates the E.H.T. panels in this station, which comprise two E.H.T. feeders and four transformer switches.

Fig. 43 is a very good example of a modern rectifier sub-station designed for supplying a tramway system with current at a pressure of 550 volts. The capacity of the station is 800 kW and outdoor transformers are used.

Fig. 44 shows the interior of this sub-station. The bulb chambers here had the doors removed to show the bulbs actually on load. Each bulb has a capacity of 150 amp. at 550 volts. The photograph shows nine of the ten bulbs in operation.

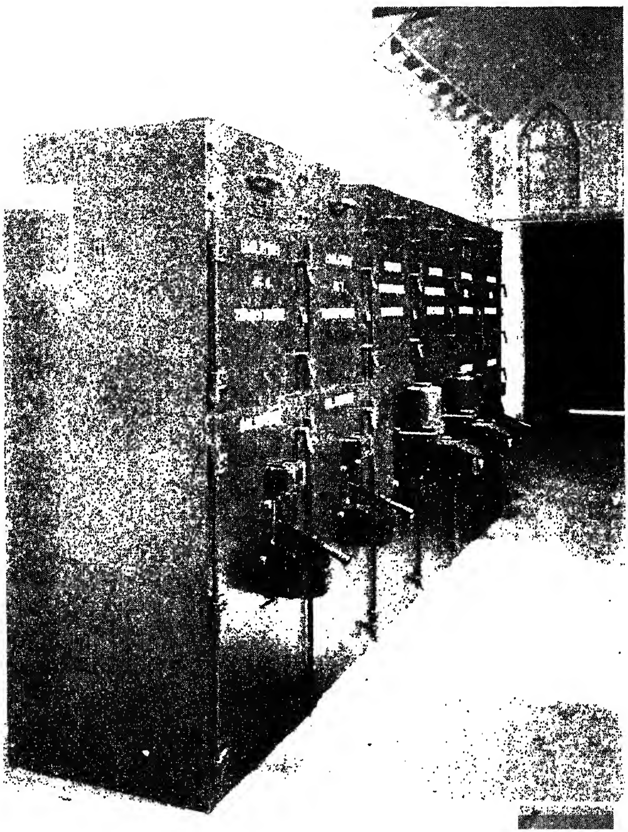


FIG. 42. E.H.T. SWITCHGEAR SUPPLYING THE TWO BANKS OF RECTIFIERS SHOWN IN FIG. 41

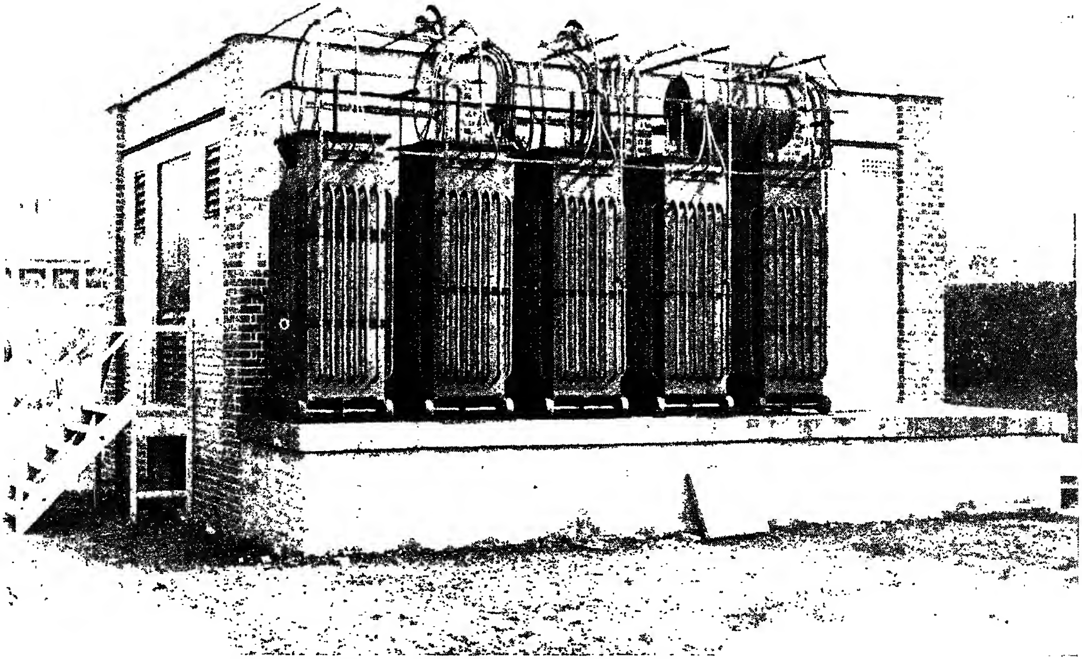


FIG. 43. TRACTION SUB-STATION WITH OUTDOOR TRANSFORMERS

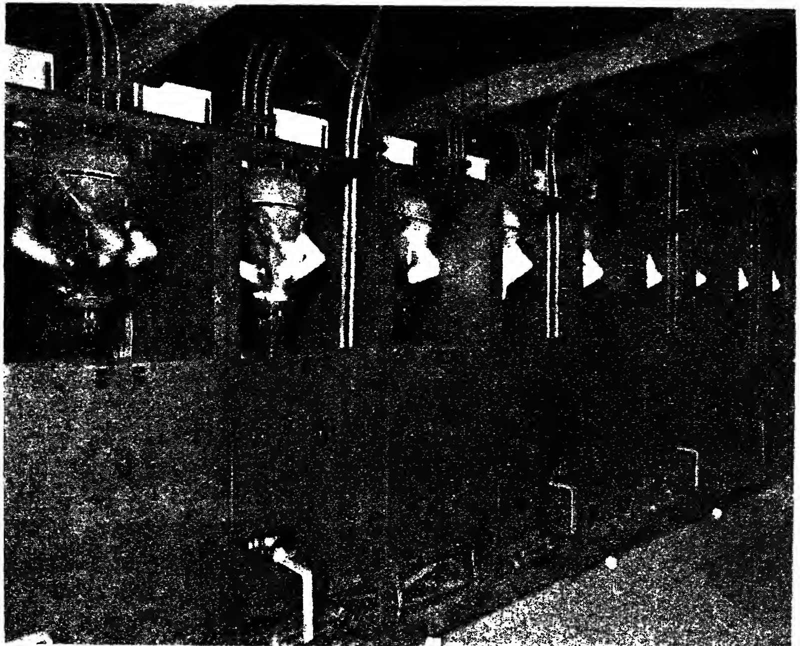


FIG. 44. INSIDE THE TRACTION SUB-STATION SHOWN IN FIG. 43

View shows bulbs on load. This station has a capacity of 800 kW

AUTOMATIC ROTARY-CONVERTOR SUB-STATIONS

In order that the reader may get a general idea of the principles involved, the operation of automatic rotary-convertor sub-stations will first be described, after which the organization of an undertaking where a large number of automatic sub-stations are employed will be dealt with.

It is felt that the reader, in this way, will be able more readily to appreciate the different points set forth in the organization than would be the case if this part were dealt with in the first place.

STARTING UP

Reference to Fig. 45 will make clear the method by which an automatic rotary convertor is started up, synchronized, and paralleled on to the direct current bars. All three phases are not shown in the drawing for the sake of simplicity and clearness.

Tappings are taken from the high tension busbars through isolators (1) to the oil switch (2), which closes automatically either on load demand, supervisory or local control, and energizes the main transformer primary winding (3) which is usually "diametrically" wound. There are tappings provided on the primary side, which permit of a voltage variation on the secondary side of 5 per cent above or below the normal voltage for which the apparatus was designed. An electrostatic earthing device operates in the event of the primary and secondary windings shorting, shutting down the unit, and preventing starting up.

The secondary winding (4) is thus made alive and everything is now ready to start the machine.

The windings of a starting motor, or pony motor as it is sometimes called, (6) are energized through a contactor (5) closing. The machine commences to rotate

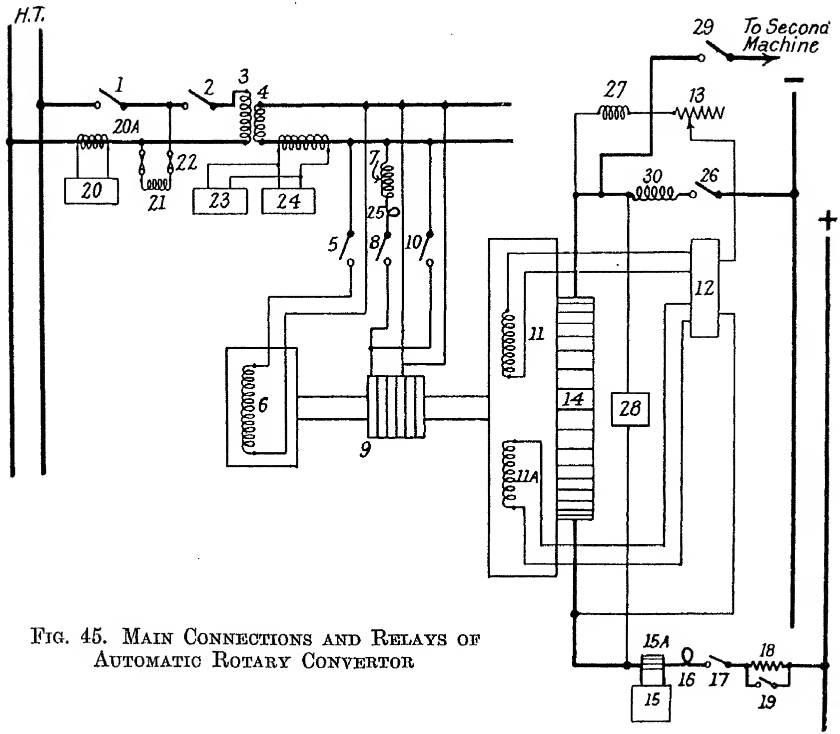


Fig. 45. Main Connections and Relays of Automatic Rotary Convertor

and build up its field (11) and (11 *A*) voltage as a direct current generator, the position of the field rheostat (13) being fixed. As the speed approaches synchronism the direct current voltage will build up and operate a field current, relay coil (27), which bridges two contacts and allows the synchronizing contactor (8) to close connecting the main transformer secondary winding (4) on to the machine slip-rings (9) through reactance coils (7).

The rush of current picks up an accelerating relay (25) and also pulls the convertor into synchronism.

When synchronous speed is reached, the current in these reactance coils decreases, allowing the accelerating relay to fall off again and to bridge two contacts which complete a circuit for the polarized relay (28), thus making sure that the machine field has built up with correct polarity.

If incorrect polarity results, the relay operates a field reversing contactor (12) which changes over, connecting the two halves of the field (11) and (11*A*) in parallel (they are normally in series, of course), causing the machine to slip a pole and the volts to die down to zero. At zero voltage, relay (12) resets, relay (25) picks up, and so on.

If correct polarity results, relay (12) allows the main running contactor (10) to close, which puts the machine direct on to the transformer when everything is then ready for paralleling on the direct current bars.

It should be mentioned here that as soon as the running contactor closes, the pony motor and synchronizing contactors both open through a set of interlocks (not shown on the diagram) on the running contactor. These open their contacts, therefore, when the latter closes.

The knife switches (17 and 26) in the positive and negative circuits respectively are always closed, and

all that now remains is for the equalizing contactor (29) to close followed by the direct current circuit breaker (17), in order to put the machine on to the direct current bars through a "buffer" resistance (18), and then the high speed circuit breaker (19) closes and short circuits the "buffer" resistance. At this point the unit is on the direct current bars. (15*A*) is a shunt across which is connected the reverse current relay (15), set to operate just below the machine motoring current, and (30) is the series field winding giving the convertor compound characteristics.

PROTECTIVE DEVICES

Before any machine may be started up a master contactor must close which prepares all future circuits, and unless this closes no operation may take place. All protective devices operate on the coil of this contactor, short circuiting the same, causing the contacts to open and shut down the machine or prevent its starting up.

Protective devices may be divided up into two groups—

1. Those which are self-resetting when the fault conditions are cleared.

2. Those which lock out the machine permanently and have to be reset by hand after the trouble has been investigated and cleared.

The latter operate through a lock-out relay, the coil of which is energized through a small auxiliary coil (which allows a small disc to fall), indicating by a number which protective device has functioned, and releases a mechanical latch that permanently short circuits the master contactor coil, and has to be reset by hand.

Fig. 46 shows how the machine is shut down. As soon as the master contactor (2) closes, a time delay relay commences to operate, and if the machine fails

to synchronize within a given time this relay will make contacts (12), energizing the lock-out relay coil (8), and thus lock out the machine by short circuiting the coil of the master contactor as stated above.

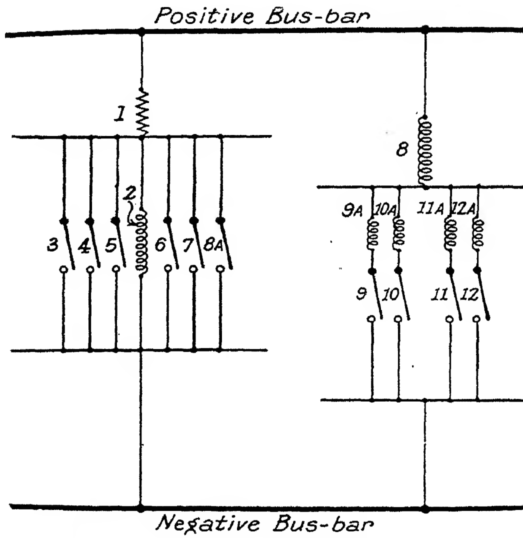


FIG. 46. PROTECTIVE RELAY CIRCUITS

SELF-RESETTING

1. Resistance.
2. Coil of master controller.
3. Shut down, machine on underload.
4. Thermostat on buffer resistance.
5. Machine temp. relay.
6. Reverse current.
7. Pilot relay to stop machine from remote station.

8*a*. Lock-out relay.

HAND RESET

8. Coil of lock-out relay.
9. A.C. overload and earth leakage.
10. Overspeed.
11. Bearing temperature.
12. Time delay for synchronizing.

9*a*, 10*a*, 11*a*, 12*a*. Coils which release numbered discs, indicating which device has operated to lock out the machine.

If the machine goes on to the direct current bars with low voltage, the reverse current relay (see Fig. 46) closes its contacts (6) and shuts down the plant. The unit will not again restart until such time as the field

current relay (27) has reset, and this will take place when the machine direct current voltage has died down.

When the sub-station load is sufficient only for one unit, any additional convertor running at the time will shut down on the underload relay, which makes its contacts (3).

Should a machine be called upon to sustain prolonged overload, a temperature relay connected to a current transformer (20 *A*) (see Fig. 45) closes its contacts (5), and the setting is so arranged that if the overload is comparatively sudden the relay will cool off proportionately quickly, but if gradual, the time taken to reset will be proportionately longer than that in the first case.

If the overload is instantaneous, such as a "dead short" circuit, outside the station, the high speed circuit breaker will clear and leave the machine feeding on to the direct current busbars through the "buffer resistances," and when these heat up, thermal elements will function and close their contacts (4). These will reset and the machine again will start up when the resistances, and therefore their thermostats, have cooled down.

A machine also may be started up or shut down from a remote station on pilot control through a pilot relay. The latter operation closing contacts (7).

Alternating current overload or earth leakage will energize a relay and close contacts (9).

Overspeed similarly will operate contacts (10).

Hot bearings will cause their thermostats to shut down the machine.

LOAD DEMAND SEQUENCE—STARTING AND STOPPING

Imagine one unit running with the load increasing, a second and perhaps a third machine is required. The

phase amperes in No. 1 machine will increase, operating a time delay relay set at a predetermined value, and cause a motor-operated controller drum to rotate, make contact and bring in another machine, at which point the relay resets; similarly a third machine is brought into service should the load require the same.

Supposing the second unit locks out during the starting-up period, the drum will pass on to the third machine segment without stopping, because the load demand is still there.

Similarly, for shutting down, a main current transformer, which measures the total sub-station load, will release a relay, which runs the controller drum in the reverse direction, thus shutting down each machine as required after a prolonged time delay, necessary on account of the fluctuating load inseparable from traction supplies.

If three machines are running and only two are required, when one of them shuts down, the high speed circuit breaker opening, inserts a resistance in the shutting-down relay which compensates for this unit being out of service, preventing another unit from shutting down until the load conditions warrant such an operation.

As mentioned previously, any machine may be started up by the remote controlling station, thus anticipating the load demand sequence of operations.

If such be the case, any unit which is put into service by this method must be shut down by the remote station, as the pilot relay is mechanically latched in and only the reverse operation will release the latch, the controller drum thus being shorted out.

The control panel at the remote controlling station shows the operator the exact position of all the plant at any instant, by means of indicating lamps connected to interlocks on the machine oil switches, direct current

breakers, and feeder circuit breakers. The load and pressure also may be read on voltmeters and ammeters connected through pilots to their appropriate points.

FEEDER CIRCUIT BREAKERS

Such circuit breakers distribute and convey the current to different points on a tramway overhead system, and are so designed as to be automatic in opening under fault conditions, and will reclose when such conditions have been eliminated.

In the event of a fault occurring, the circuit breakers in question will clear and remain open until such time as the cause of their operation is removed.

An arrangement exists whereby the main connection on a feeder circuit breaker forms a primary winding, and a secondary winding around this will have a current induced in it under a sudden short circuit condition, due to the sudden rate of change of flux, so operating a relay whose contacts are in series with the main breaker hold-on coil, which opens and thus clears the line.

Then a feeder resistance measuring relay, connected across the breaker contacts, will operate and will not reset until the resistance of the load outside the sub-station is normal, when after a time interval the line will be made alive again. This principle is applied in modified forms for both through feeders and stub-end feeders.

Should the fault be sufficiently heavy as to shut down the whole sub-station and trip all the feeder circuit breakers in addition, so that the direct current busbars are dead, a change-over contactor is fitted containing two coils, one of which is wired up to the "Through Feeder," i.e. the feeder which connects the sub-station in parallel with another sub-station, the other being connected across the sub-station busbars.

When the distant sub-station through feeder is closed, this two-way contactor will throw over and the circuit breaker will close, thus supplying current to the busbars, making it possible for the other feeder circuit breakers to reclose before a machine is run up. The supply, therefore, will be maintained from this distant sub-station.

HIGH SPEED CIRCUIT BREAKERS

As the name indicates, these will break a circuit at very high speeds and clear a machine before the current has had time to rise sufficiently to cause damage.

A direct current relay makes its contacts (3) in Fig. 47 and energizes an auxiliary contactor coil (2) through suitable fuses (5) and (1). The contacts (9) close and short circuit the hold-on coil (7) of the high-speed circuit breaker; (4) and (8) are fuses in this circuit, and (6) a resistance. When the current relay resets, the contacts (3) will open, de-energizing the coil (2) when the contacts (9) will open, allowing the closing coil (not shown) to function and the hold-on coil again to operate when the breaker closes.

The hold-on coil has a laminated iron core open at one end, into which air gap, a small coil of low ohmic resistance, connected across the series blow-out coils, is inserted.

When the coil (7) is short circuited and the breaker commences to open, the series coils become highly inductive and a heavy current passes through this impulse coil as it is termed, diverting the flux from the main path, thus allowing the movable iron armature to break away at once. The flux otherwise would be slow to die down and the breaker would not be high speed in its action. Fig. 48 will show this operation clearly. It is important that the flux due to the impulse coil be in the same direction as the flux produced by the hold-on coils.

Fig. 49 shows such a traction sub-station as described. In the remote background will be seen the top of the high tension supply cubicles; immediately in front of these, the cooling tubes on one side of the main transformer.

Immediately behind the machines is the alternating current starting panel complete with power factor meter,

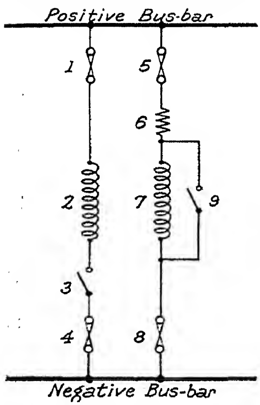


FIG. 47. HIGH-SPEED CIRCUIT BREAKER OPERATING CIRCUITS

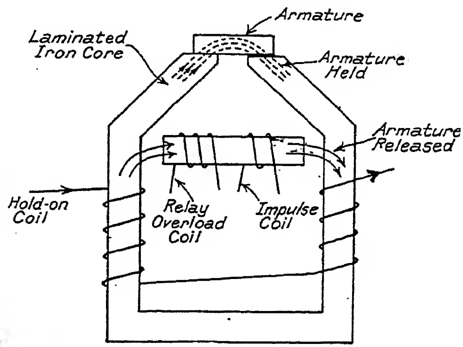


FIG. 48. HIGH-SPEED CIRCUIT BREAKER ACTION

phase ammeter with connections taken from a current transformer, high tension voltmeter (operated from a potential transformer), and synchronizing voltmeter on left of panel situated between the synchronizing lamps.

Opposite this panel is the pony motor and rotary convertor. The near end bearing contains the centrifugal over-speed device and oscillating gear.

The apparatus against the far wall is the Board of Trade panel containing three watt-hour meters, line leakage test ammeter and recorders for rail point drop and earth leakage.

FIG. 49. AUTOMATIC ROTARY CONVERTOR TRACTION SUB-STATION

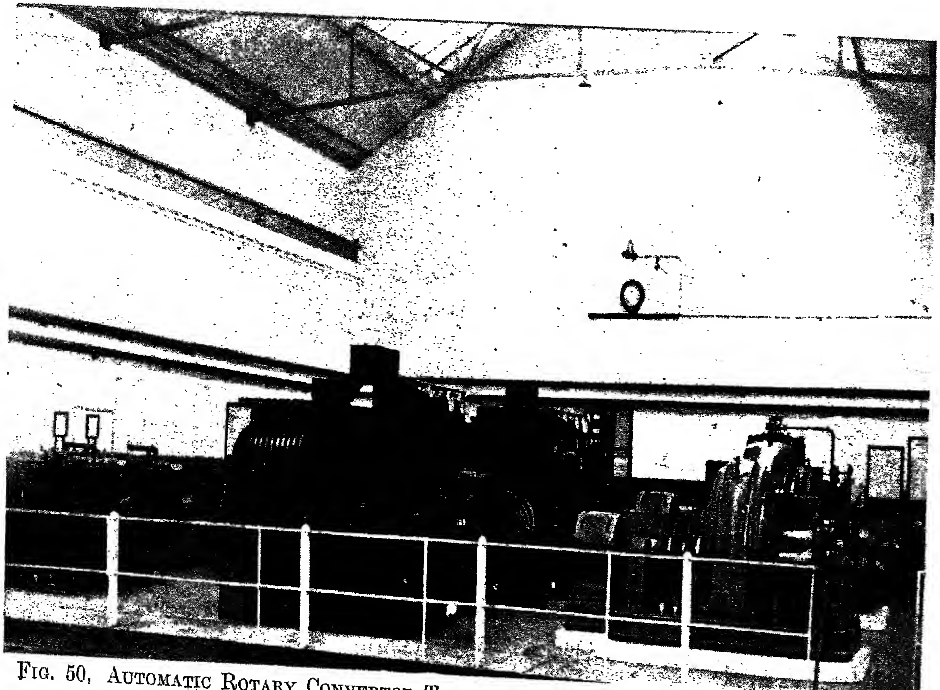


Fig. 50, Automatic Rotary Convertor Three-wire Lighting and Power Sub-station

On the extreme right of the picture is the direct current side of the rotary convertor. The high-speed breaker hold-on coil will be observed together with the magnetic blow-out coils and arc chute.

This, then, is a typical sub-station, and should give the reader a very fair idea of the general layout of such sub-stations.

Fig. 50 gives a side view of another typical lighting and power sub-station. It will be noticed that the high tension switchgear is of the armour clad type.

Fig. 51 shows the direct current control panels for the rotary convertor, illustrated in Fig. 49. The "Buffer" resistances, already mentioned, will be observed above the panels, together with the thermal elements which will operate when the resistances become hot, due to their being called upon to carry a heavy current. Then we have the two-pole machine circuit breakers (positive and negative) with their interlocks and hold-on coils. The small coil on the right of the breakers is a shunt trip coil which functions only when the contactor is latched in mechanically. Under fault conditions, the circuit of the coil is completed by the closing of contacts by means of the operating of the electro-magnetic overload device, which energizes the coil and trips the catch holding the breaker in position. When the apparatus is held in electrically, this shunt trip coil is prevented from operating by means of interlocks, and the electro-magnetic overload device influences the hold-on coil direct.

The reverse current relays are clearly indicated as also is the voltage regulating relay, which is the long box-like case situated immediately under the shunt trip coil.

The hand wheels for the field regulators are shown on the bottom panels. They are mechanically coupled together behind the board, and normally are driven

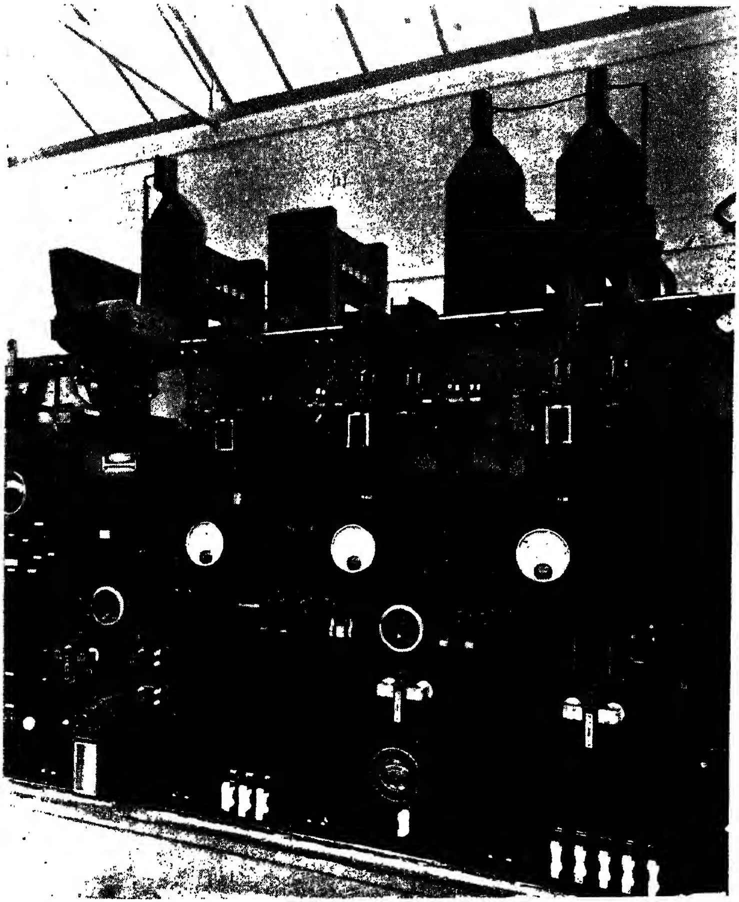


FIG. 51. DIRECT CURRENT CONTROL BOARD OF AUTOMATIC ROTARY CONVERTOR SUB-STATION GIVEN IN FIG. 49

through reduction gearing by a small direct current motor energized by means of contactors (mechanically interlocked so that they will not close at the same instant), which are energized by the voltage regulating relay.

OTHER TYPES OF AUTOMATIC ROTARY CONVERTOR SUB-STATIONS

The author has deemed it better to describe one type of automatic plant *in extenso*, so far as its simplest form makes possible. Even so, numerous important details have been omitted and interlocks (which are very important) have been ignored, in order to give the reader a clear idea as to the main principles involved and the general scheme of things.

To include everything, by making this description entirely comprehensive would serve only to confuse the reader.

Nevertheless, the reader may be interested in some of the other methods adopted by makers. Although the fundamental principles are the same, the execution of those principles are widely divergent. The relays in use are variant, no two types are similar in their wiring and layout, and there are several methods in use for remote and supervisory control.

The supervisory control method will be discussed later.

Methods of Synchronizing. A common method of synchronizing a rotary convertor is that just described with pony motor and reactance coils.

Another method, however, may be of interest. The pony motor in this case is wound with the same number of poles as, and connected in series with, the rotary convertor armature, and tappings are taken off the former. When the oil switch closes the pony motor contactor, which is already in the closed position, allows

the machine to rotate and build up its pressure. When this reaches a value of about 60 volts, a synchronizing contactor relay operates, tripping the pony motor contactor immediately prior to closing the synchronizing contactor. The reason for this is, that heavy circulating currents would flow if both were closed at the same instant.

The synchronizing contactor closing cuts out a percentage of the pony motor winding, and the resultant rush of current increases the speed of the machine to that of synchronism. When the direct current pressure registers about 80 volts, a relay operates, energizes a field reversing contactor and reverses the field, whether the polarity is correct or not.

The rotary then starts to slip poles, quickly at first, but gradually decreasing in frequency as synchronous speed is approached. When the unit has built up a pressure of about 100 volts in the correct direction, the field reversing contactor is restored to normal, the running contactor closes, and, after a short time delay, opens the synchronizing contactor through interlocks.

A further method, called tap starting, is by means of tappings of different voltages taken off the main transformer. This, of course, involves a device for lifting the direct current brushgear, but is quite a favourite method in automatic sub-stations.

Automatic Oil Switches. The general trend of manufacturers' design leans towards the motor-operated type of high-tension oil switch.

A contactor closes, energizing a three-phase alternating current induction motor which closes the oil switch.

The methods by which such a switch is closed are many. Several types will be mentioned quite briefly.

1. A heavy fly-wheel is fixed on the motor shaft,

and, when full speed is reached, a lever, operated by centrifugal force, makes contact and permits the no-volt coil to become energized. The plunger thus being drawn up by the magnetic flux permits a catch to engage with a lever connected to the main oil switch ; this closes ; the motor is de-energized by the contactor opening through interlocks which break contact when the closing operation is completed.

The fly-wheel tends to keep the mechanism up to full speed while the heavy switch is being closed. Otherwise, the motor would slow up, and the centrifugal lever resetting, would thus make the operation abortive.

When the switch closes, a set of interlocks make contact which keep the no-volt coil energized, so that it is independent of the centrifugal lever.

The de-energizing of the no-volt coil by any of the protective devices will cause the oil switch to open, and thus disconnect the machine from the alternating current busbars.

2. The no-volt coil is always energized, so long as no protective devices have operated, and the motor winds up the switch through a system of gears. This process is slower than method (1).

3. A motor rotates, and, as full speed is reached, a set of governor balls expand raising a lever permitting the oil-switch closing mechanism to engage and close the switch, when the motor is de-energized through interlocks and the apparatus may be released automatically when the no-volt coil is de-energized.

The above types are slow in their closing motion as compared to the direct current solenoid operated type. But all varieties of switches are quick in their breaking operation, and almost invariably the holding mechanism is released by de-energizing the no-volt release coil. It is, therefore, of the utmost importance that this unit be inspected most carefully at frequent

intervals, in order to ascertain that the plunger or armature movement is not "sticky" in its action.

Numerous protective interlocks usually are attached to the movable parts to ensure correct sequence of operation, so that in the event of a contactor sticking in the closed position, due to some mechanical fault generally, the starting up sequence will not function.

It is a good practice, when the switch closes, for it only to charge the main transformer and not to supply the starting current to the pony motor at the same instant. Because, if a failure of the mechanism (the adjustment of which is very delicate) occurs, the oil switch contacts are called upon to break a very heavy current due to the amount required for charging the main transformer, together with the initial starting torque current required by the pony motor. The sum of these two currents with the unavoidable poor power factor often exceeds the full load current of the machine.

Starting-up Sequence. A favourite method of starting up is by means of a controller drum, having spaced metal segments of various lengths placed round its periphery. The whole is motor operated through reduction gearing, and a line of cantilever type of contacts fitted above each row of segments make contact from time to time in their proper order as required, when the drum rotates.

Thus, the sequence of operation is permanently fixed, and it is so arranged that a failure of any relay or mechanism to operate during any part of the sequence will stop the drum at that point, and the machine will lock out. This provides an additional check on the indicating lock-out relay as to where the fault lies.

The drum stops at several points in order to allow time for the machine to gain speed to build up its voltage, synchronize, etc. The pauses are brought about

by gaps in the segment supplying the driving motor with current. These gaps are bridged by relays operating, thus allowing the drum again to rotate and the sequence to proceed.

Finally, when the machine is shut down, the drum returns to a position ready for starting up again.

An electrically-operated brake, the coil of which is in series with the motor circuit, is lifted while the motor is energized, but as soon as the circuit is broken a spring pulls down a lever which stops the motor instantaneously. In this manner, over-running on to the next segment is prevented before conditions are ready for such a step.

Excitation. The machine described in more or less detail was self-excited, but some types of machines are separately excited by a motor generator through an auxiliary winding on the main field poles, in order to ensure correct polarity before switching over on to the main field and leaving the machine self excited. Greater assurance of correct polarity is obtained, but even so the field polarity is further checked by a polarized relay. It is just as well, because the author knew and had experience of a case where a separately excited machine attempted to build up with wrong polarity but, fortunately, the current in the rotary convertor armature kept on wiping out the wrong field before it built up too strongly. The trouble was caused by weak contact between the direct current brushes and the commutator of the auxiliary motor generator.

Thermal Relays for Time Delays. Thermal relays differ in design. Some depend upon the expansion of a liquid in a container to close or open sets of contacts through a mechanism of levers, others embrace the bi-metal strip, consisting of two dissimilar metals with different coefficients of expansion clamped at one end

and bound together at the other, but free to move up and down.

Through these strips a heavy current is passed from a small auto-transformer. Heating is produced and the strip warps in an upward direction where it makes a contact, energizing a small contactor which closes and thus cuts out the auto-transformer.

The time delay action is obtained during the cooling of the strips, when the metals gradually return to their original position and make contact.

PARALLELING ON TO DIRECT CURRENT BUSBARS

The reader will remember that the traction machine described, paralleled on to the direct current busbars through a "buffer" resistance; another method especially useful for machines supplying current for three-wire lighting and power systems is for the unit actually to parallel direct on to the bars, as in a manually-operated station, by means of a paralleling relay which ensures that the voltage of the incoming machine is slightly higher than the existing busbar pressure.

The relay is of the balanced beam type. There are two iron-cored coils, one being connected across the busbars, i.e. positive to negative, through suitable fuses, and the other across the machine terminals.

They are set so that the machine coil will overcome the pull of the busbar coil when the pressure difference between the machine and the busbar is, say, 3 volts. This voltage difference is constant whatever may be the supply pressure. Great care must be taken in setting this relay as temperature plays a large part in its successful operation, and temperature for this purpose does not depend solely upon ambient temperature, but upon the heat generated inside the relay case, from the energized coils.

Once set to the correct value, the relay should function perfectly. It must be borne in mind when setting this type of relay, that certain conditions must be observed.

Such things as (*a*) after standing all night a machine is started up—one coil is cold and the other hot, (*b*) a machine has been running all morning, and is shut down during the dinner hour—both coils hot. Consequently, a mean between the two has to be struck.

Voltage Regulation. Various methods are adopted for keeping the supply voltage at a constant value. An induction regulator connected in the alternating current side of the machine may be employed. This varies the low tension alternating current voltage supply to the machine, and, consequently, the direct current voltage, as there is a definite relationship between the two. The field rheostat is used only to vary the power factor. Similarly, by reactance control the pressure may be varied by means of the field rheostat only, causing variation of the phase angle and, therefore, the direct current voltage. Machines usually are designed to give, say, a ·95 leading power factor at full load. In any case, a relay is required which will keep the direct current voltage at a constant value under all load conditions.

For such a relay, some manufacturers prefer the balanced beam type with two iron-cored coils connected in series across the supply outers, the pull of each coil on the beam being counterbalanced by a spring on each beam, others prefer a single coil, similarly connected, with a floating armature working against a spring, the contacts in this case are fixed to the armature.

In any case, the operation depends upon the principle that when the pressure is high, more current is taken by the coil, causing greater magnetic saturation

of the iron, so that the beam or armature moves downwards and contact is made to energize the field rheostat motor contactor coil, which operates to cut in more resistance in the field circuit, thus lowering the pressure and vice versa.

Temperature playing an important part in the setting of such a relay, a device is embraced whereby the greater part of the necessary total resistance is situated outside the relay case. The relay contacts when made, merely bridge a resistance in series with another and intermediate relay, so that the current in the coil of the latter is increased sufficiently to pull over a movable arm, this operating the field rheostat motor contactor through a time delay relay.

The type described has a moving iron armature and is extremely sensitive. The platinum contacts are set close together in order that a very small movement of the armature due to a very small variation in pressure, will operate the intermediate relay. The time delay is necessary to prevent continuous operation of the regulator. The main relay contacts, on account of bridging a resistance, only break very small currents, and being platinum or platinum alloy, do not become dirty and cause trouble. The resultant voltage line as shown by the recorder is very good indeed, and approximates very closely to a straight line.

End stops are fitted to the field regulator. These are merely electrical switches which are normally closed, but are opened mechanically by means of a lever, if the moving arm on the regulator approaches either end. When open, these switches open circuit the coil of the motor contactor and prevent the regulator over-running.

Usually, the contactors mentioned above are mechanically interlocked, so that both cannot close together and cause trouble.

FULL LOAD OPERATIONS

1. Maximum Current Relay. If the load on one machine becomes excessive, and there are no more machines to be put into service, i.e. supposing No. 2 convertor in a two-unit sub-station fails to synchronize and locks out when coming in on load demand, then, if the load demand is increasing rapidly, in order to prevent the plant from being seriously overloaded with a probability that the machine temperature relay will operate and lock it out, a current relay connected across a shunt will function, its contacts making will cause the machine voltage to be lowered by operating the field rheostat, until such time as the load is decreased sufficiently for the movable contact of this relay to " float " between its two fixed contacts. Thus, the automatic feature of voltage regulation will be put out of service, until such time as the load has fallen sufficiently for the relay to reset and restore the automatic regulation system to normal.

The above type of relay has been instrumental in preventing a total shut down on more than one occasion to the author's knowledge.

2. Machine Temperature Relay. If the machine armature winding becomes excessively hot due to prolonged overload, or to carrying a heavy wattless current due to a bad power factor, a relay, connected to the secondary side of a current transformer in the alternating current supply circuit to the convertor, will operate with a time delay proportional to the length of time the armature takes to heat up, and to the amount of overload producing the heating effect. In other words, the relay is set to operate according to the convertor's characteristics. Consequently, the machine will shut down until such time as the relay resets, when the unit will start up again.

The relay usually is set to allow 25 per cent overload for 2 hours, 50 per cent overload for 1 hour, and 100 per cent overload for 2 min.

3. Second Machine Starting up on Load Demand. When one unit is fully loaded and additional plant is required, a current relay connected across a shunt in the machine direct current supply circuit operates, and energizes a time delay relay, which sets the starting mechanism in motion. The time delay relay is necessary, so that a sudden but temporary fall in pressure will not start up the plant. Two minutes delay is usually allowed, during which period of time, if the current falls again, the relays mentioned will reset without the extra plant having started up.

4. Two or More Machines Running in Parallel on Load. If two or more machines are running, it is desirable that they should share the load equally. In order to do this, one unit is made the "master" controller and, when running, the voltage regulating relays of subsequent units are put out of commission automatically by the closing of a contactor breaking their operating circuits, only the voltage regulating relay of the "master" unit functioning. The other machines follow its lead by means of a current relay (balanced beam type) which, when the load increases on the "master" unit, causes all the other machines to take additional load, raising their pressures in proportion and vice versa.

Several methods are adopted to attain this end—

(*a*) A relay with two coils, tapped across the field circuits of two machines balance up the voltages thus measured. The beam is set so that the voltage difference is kept at a minimum.

(*b*) In sub-stations with three or more machines, another method is for the second unit to deal with all excess load above the full load of the first convertor,

until both machines are fully loaded, any further load being taken up by the third unit, and so on.

In each case the preceding units are kept fully loaded, irrespective of pressure regulation, the incoming machine dealing with voltage regulation.

(*c*) Where buffer resistances are employed, the field rheostats are locked together mechanically, either by a system of gears or by a chain drive, operated by one motor. In this case, one voltage regulating relay only is required to operate the rheostats.

Differences in the characteristics of machines are compensated for by a small hand-operated rheostat in series with each main rheostat, the positions of which are fixed on test, and give the desired result, viz., each unit shares the load equally.

Overload Operations. Should a sudden short circuit condition arise sufficiently severe to operate the overload relay on the direct current side, the operation of this relay will cause all the machine circuit breakers to open simultaneously, and when the conditions are normal these circuit breakers will reclose automatically at the same instant.

Underload Operations. As the load demand falls to a value which can be dealt with by fewer units, an underload current relay connected across a shunt makes its contacts, energizing a time delay relay, exactly similar to that employed for starting up on load demand, and causes each machine to shut down as required.

One method adopted is that the unit which has been running longest is the first to drop out, and matters are arranged so that the last machine has to be shut down by supervisory control and not by the underload relay. This scheme is advisable because, even though the load is comparatively small, the feed from the manually-operated sub-station in parallel with which the automatic sub-station is running, would allow the

pressure to fall considerably under certain network conditions. It is necessary, therefore, to retain one unit in service, to keep up the pressure, longer than would be the case if it were under the control of the underload relay.

In addition, the pressure drop would be still more noticeable as the voltage regulating relays have a compound winding connected across a shunt, which automatically boosts up the pressure with increase of load by increasing the flux in the iron core, causing greater attraction of the beam.

The sequence for starting up or shutting down may be altered whenever required, either by changing over a system of plugs, operation by supervisory control, or by means of relays.

SUPERVISORY CONTROL

Modern automatic rotary convertor sub-stations are fitted with some form of supervisory or remote control.

An ammeter and voltmeter are connected to pilot wires at the controlling sub-station, the former may be switched on to any machine and load readings taken. Indicating lamps showing " in " and " out " are wired up to all feeder circuit breakers, each machine oil switch and direct current circuit breaker, so that the engineer at the manually-operated sub-station knows at any instant the exact position of all the plant under his control.

A pilot wire for each indicating and operating circuit would entail a multi-cored cable, the cost of which would be prohibitive, especially over long distance control.

The author has had some experience of the three-pilot wire method of control, which is the one usually adopted, so that a brief description of one type in use and comments on other types may be of interest to the reader.

One will readily appreciate that the system is very complicated and delicate, requiring careful supervision and handling.

It would be more than the scope of this book to deal intimately with each variety in detail, so that a brief description of the principles of each will have to suffice.

Broadly speaking, therefore, they may be divided up into two main groups—

1. The automatic impulse type, such as is used on automatic telephone exchanges, and

2. The direct operation of relays by means of comparatively heavy currents passing along the pilots.

The difference between the two is that with supervisory control the whole plant is controlled, including feeder circuit breakers, and machines may be allowed to start up automatically on load demand, etc., or units and feeder circuit breakers may be locked out of service, whereas with remote control, machines may be started up and shut down only, so that unless more pilot wires are added, the feeder circuit breakers merely indicate "in" or "out." The latter system usually functions on a multi-cored pilot, whereas the former operates on three pilot wires only.

Group (1). (*a*) A cabinet on which is mounted small indicating lamps fed from a secondary battery which is always under trickle charge through resistances, and a relay which cuts off the charge when an operation takes place or the battery voltage becomes too high, has also mounted on it keys to control the main plant in the remote automatic sub-station.

On one of these keys being turned by hand, a clockwork spring is wound up and, on release, returns slowly to its original position, tapping out a code of impulses by means of making and breaking contacts while so doing. The contacts are made to function by a system

of gears driven by the clockwork spring. Another secondary battery supplies the current for the impulses.

Any convenient coding may be used.

These coded impulses, therefore, are transmitted over the pilot wires through relays to the automatic sub-station, where they are received by selector switches.

Each impulse causes a small wheel, on which contacts are mounted, to be notched round by means of solenoids. When the final impulse is reached, the wheel pauses on that particular contact, operates a power relay, and then resets.

The power relay contacts supply the main current for the particular operation.

Suppose the code to be 7—3—11, the figures represent the number of consecutive impulses, i.e. seven, pause; three, pause; eleven, pause—reset. Any other combination will not operate the power relay, because the selector switch will not come to rest on its proper contact—it is, so to speak, thrown out of gear. It is on this principle of coded impulses then, that the apparatus functions.

As an example, let us suppose that it is required to start up a machine. The appropriate key will be turned, impulses are transmitted over the pilots, the power relay coil is energized momentarily, causing the relay contacts to throw over from one position to another, and the starting up sequence is thus put into service.

The high-tension oil switch closes, making an interlock which sets in motion, through small relays, a constant speed motor driving a shaft on which are mounted a number of toothed wheels connected to the shaft through clutches.

The wheels are held stationary by a solenoid-operated trigger finger, except the one which is released by the operation of the oil switch closing. The interlock thus made, energizes a small solenoid which releases the

trigger finger allowing the wheel to rotate and tap out a code of impulses. This is accomplished by the teeth on the wheel, depressing contacts which make and break. The pauses between each code figure are supplied by blanking off a number of teeth. The code, then, is transmitted over the pilot wires and operates a small polarized relay at the controlling station end. Contacts are made which causes a "red" indicating lamp to light up showing that the switch is in, and a green lamp, which showed the switch was out, to be extinguished. A similar function is carried out by another wheel when the machine direct current circuit breakers close. Likewise, the feeder circuit breakers may be operated and send back an indication of their position as described above.

Any change of signal either produced by turning a key, or by the automatic operation of any part of the plant, is indicated by the ringing of an alarm bell and the lighting up of a small pilot lamp at the control station.

The bell-ringing may be stopped by moving a small switch provided for that purpose, which resets the bell relay after the operation has come through correctly.

To shut down a machine, the corresponding key is turned, which again causes the power relay to throw over its contacts and the unit drops out of service.

The interlocks on the oil switch and direct current circuit breakers again change over, but on this occasion the time interval between the two is infinitely small, and one would expect both sets of coded impulses to go through simultaneously, with a consequent mix-up of signals, but this is not the case.

Each code goes through completely before the next one starts. This desirable state of affairs is obtained by the catches on the toothed wheels not releasing their respective wheels while any one other is working.

Interlocks accomplish this fact, so that no matter how many indications attempt to come through together, only one at a time will be successful, and all others will await their turn.

In some automatic sub-stations it is advisable to allow the first machine to start up itself, i.e. by a busbar voltage relay operating when the pressure drops low enough over a period determined by the setting of a time delay relay.

This scheme applies very particularly to a sub-station situated where the load comes on very quickly. Should the supervisory gear fail for any reason to start up a machine, it may be switched over to "automatic," and the plant will start up itself as described above.

This is important because the through feeders may be overloaded to an alarming extent, and even the fuses at the manually-operated sub-station or inter-connector fuses blow, with a consequent failure of supply, before an attendant can arrive at the sub-station to start up by hand.

(*b*) The other type of supervisory control gear works on a similar principle, but the execution is different. The operating key, when turned, itself does not tap out the impulse code, but energizes small contactors which, by energizing and de-energizing one another, tap out the necessary impulses which operate a rotary switch at the controlling station. A similar switch rotates in synchronism at the automatic sub-station, and stops at a given point where contact is made to energize the power relay and thus the plant, through auxiliary contactors. A check back circuit is employed whereby an operation may take place only if the particular mechanism to be worked is ready for functioning, i.e. if it is desired to close a circuit breaker and the same is already closed (which might happen where a wrong indication is showing, due to a dirty interlock, loose

connection, etc.), the supervisory will not act, as the check circuit is broken.

In addition, if any part of the plant functions without the key being turned, an alarm bell will ring to indicate that a change has taken place and a white lamp will glow. Both continue to function until the key concerned is changed over to the new position corresponding with the indicated position of the switch.

A test key is provided which, in the event of wrong indications, should set going the rotary switches, etc., and so restore everything to its proper indications. This key is used if any doubt is entertained as to the position of a switch.

The essential difference between the two types of apparatus described, is that the former sends out impulses in code, and the latter sends out only a series of impulses which continue to operate the rotary switch until a certain pre-determined point is reached by both switches, when the operation will cease.

Group (2). In this type of control gear, the pilots, as already stated, carry comparatively large currents, either alternating current or direct current which operate particular relays. The plant is controlled by push buttons, on each one of which are numerous interlocks, and these when depressed, make and break a very great combination of circuits. The fact that some relays operate on alternating current and some on direct current, gives a very wide range of useful circuits.

Fig. 52 shows a 1000 kW rotary convertor running on load with the direct current panels in the background.

In the foreground will be noticed the supervisory control cabinet.

The top two shelves contain the constant speed motors for sending back indications as already described and the bottom shelf houses the selector switches.

Fig. 53 gives a more detailed view of such a cabinet.

The shelves are designed for removal as a complete unit, and contact is made by means of jacks, which prevent disturbance to the wiring when it is desired to remove them for inspection or cleaning purposes.

Fig. 54 shows the supervisory control cabinet at

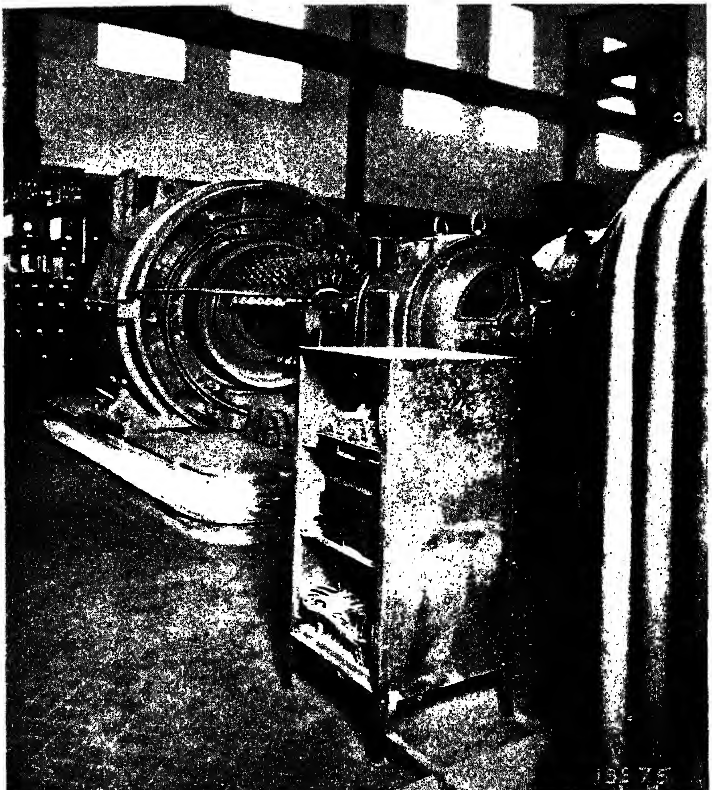


FIG. 52. SUPERVISORY CONTROL PANEL AT AUTOMATIC ROTARY CONVERTOR SUB-STATION

the controlling station end. The small panel mounted above is the one containing the control keys and indicating lamps. The two whitened portions are confined to machines, while the central and bottom sections are allotted to the feeder circuit breakers.

Mounted on top of this panel is the pilot light which lights up when a change of indication occurs, and to the right is the alarm bell control which functions at the same time as the lamp. The selector switches are clearly shown in their glass, dust proof cases, on the two bottom shelves. Mounted on the wall at the side are the small circuit breakers which operate in the event of a fault on the wiring, etc.

Manual Operation of a Rotary Convertor. The possibility is not entirely remote that a failure of automatic or supervisory gear may occur, so that in order to maintain supply it would be necessary to start up a rotary convertor by manual methods.

The reader, therefore, may be interested in a brief account of the procedure adopted in such a case.

Of course, each type of machine together with its automatic features entails particular detail work before such an operation may be accomplished, consequently the general procedure only will be set down, without special reference to any one type of sub-station equipment.

It is usual to have fitted mechanical latches to all main contactors, oil switches, and circuit breakers, Normally, these latches are "clear" under automatic working conditions.

When, however, a machine is to be started up manually, these devices are prepared for use before commencing the sequence of starting up. The procedure is as follows—

1. The field rheostat is set to the correct position for synchronizing.

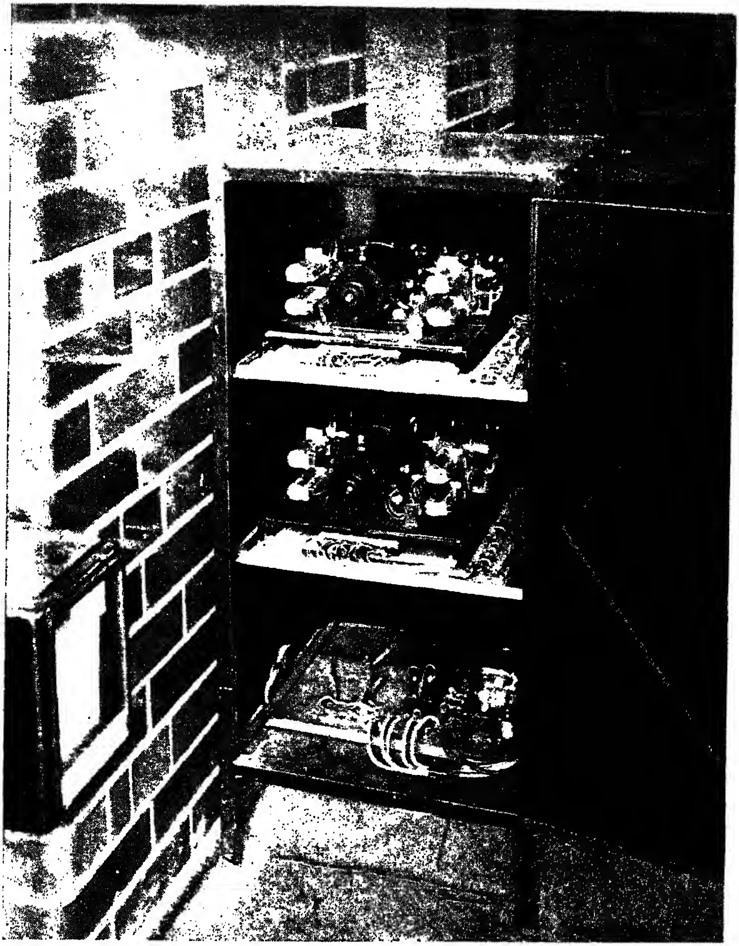


FIG. 53. ANOTHER VIEW OF SUPERVISORY CONTROL PANEL

2. The main E.H.T. oil switch is closed after opening such appropriate knife switches as may be necessary for complete manual working.

3. The pony motor contactor is then closed by a lever specially provided for the purpose, and is held in mechanically by means of the latch. The machine commences to rotate and build up its field, either by a motor-generator feeding a teaser field or by self-excitation.

4. At a certain pressure, the synchronizing contactor is closed, followed by—

5. The closing of the running contactor when the convertor is up to synchronism.

This point is determined when the lamps, connected in series across the fixed and movable contacts in one phase of the open-running contactor, are not glowing.

It is important that the lighting and extinguishing of these lamps should have decreased considerably in frequency before the contactor is closed, otherwise the machine will not have reached synchronous speed, and, in addition, there is a danger of closing in out of phase.

The convertor thus synchronized, the pony motor and synchronizing contactors having been opened, the machine direct current pressure may be adjusted now so that its value is slightly in excess of the busbar pressure. At this point the unit may be paralleled on to the direct current busbars by closing the appropriate contactors, and thus take up load.

THE ORGANIZATION OF AUTOMATIC SUB-STATIONS

Where a large number of automatic rotary convertor, rectifier, and static transformer sub-stations are placed at different points in the network of a large electricity

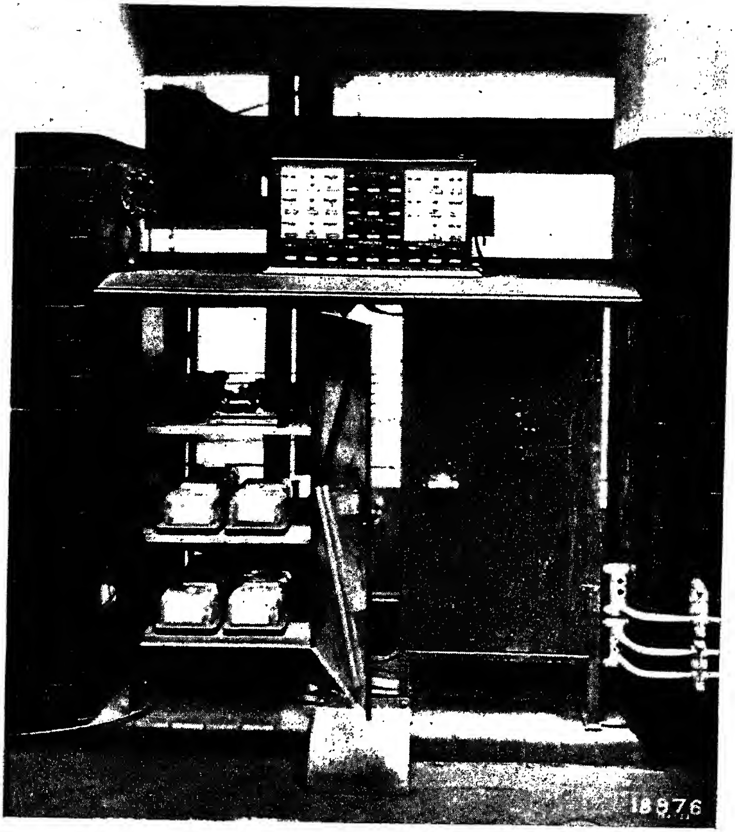


FIG. 54. SUPERVISORY CONTROL PANEL AT CONTROLLING STATION

supply undertaking, the organization of the available staff, workmen, and spares, together with a system of records, is of the first importance.

So much so, in fact, that reliability of supply may depend entirely for success or failure upon its efficient or deficient handling.

For example, suppose a breakdown occurs at any sub-station, if an attendant, or some responsible person is not always and immediately available, a lengthy discontinuity of supply may result. In addition, should recorders, etc., not be in working order, a true and correct diagnosis of the trouble and its cause, particularly the latter, may not be forthcoming.

Consequently, it is the author's intention briefly to set down a system for the efficient running and maintenance of such a distribution.

In the first place, it is advantageous to divide up the automatic sub-stations into "areas" with a junior engineer or inspector over each, and further to subdivide each area into "districts" to which are appointed two attendants, working two shifts, i.e. 7 a.m. to 3 p.m. and 3 to 11 p.m., during which times they take charge of and work each "district."

The 7 a.m. to 3 p.m. shift is essentially a period when plant may best be shut down and isolated for cleaning purposes.

The 3 p.m. to 11 p.m. shift is one during which sub-stations are visited in rotation, at the discretion of the attendant and all plant is inspected and switched in as required in readiness for the peak load demand.

During the peak load, attendants observe the operation of plant under their charge, take readings and enter them up in a log book provided for that purpose in all sub-stations.

It is advisable to provide a labourer on each "district" to assist in cleaning the floors, cable trenches, etc.

Each attendant has a certain number of substations allotted to him and he is held entirely responsible for their cleanliness and good operation, also to see that the full complement of spares, notices, ambulance requisites, etc., is complete, and connections are tight and in order.

Duties of Attendants. Attendants visiting automatic sub-stations have to be specially vigilant during their visits, as they may often be the means of preventing trouble occurring by noticing minute symptoms and taking steps to prevent the development of such indications. They cannot be too careful or too thorough, for there is so much more which may go wrong in this type of sub-station than in manually-operated sub-stations.

Cleanliness of the station plant is a matter of the first importance, and neglect of this branch of the work may prove disastrous. This being so, a labourer is allocated periodically to each attendant during his cleaning shift, and all plant upon which this man is instructed to work must be isolated and made "dead" before operations are commenced, and he must not be allowed to work in a place where there is likely to be any part "alive," or if there is the slightest danger of breakage due to rough handling, etc.

The attendant is responsible for the work of this man, to see that instructions are obeyed, to make plant "dead" for him, to work with him, and, finally, to check over all work carried out before restoring to normal.

Slate panels should be kept polished and free from dirt between contacts, all switchgear must be wiped over, and contacts cleaned up where necessary. Some manufacturers, however, strongly advocate that contactor contacts should not be faced up unless badly pitted, because they say a better contact surface results when the rough surfaces unite.

That cable trenches be kept clear of dirt and oily waste material is important, on account of severe fires which are liable to occur and spread rapidly with considerable damage resulting, if such material is allowed to accumulate.

When any switching operations, either E.H.T. or L.T., are carried out, an attendant should visit the sub-station affected, so that should anything go wrong with any part of the plant during such operations, no interruption of supply will occur.

It is of the greatest importance that periodic inspection of feeder circuit-breaker panels be carried out, so that all loose connections may be tightened up, relay contacts overhauled and cleaned up where necessary, and the relays themselves tested.

The author has found that before a sub-station is finally accepted and taken over from the manufacturers, such connections should be examined thoroughly in order to make sure that lock nuts are fitted and, where more than one wire is attached to a terminal, that proper flag lugs are sweated on and that a spacing washer is inserted between each lug in order to obtain the best possible electrical contact.

A reliable inspector for such work as mentioned above is essential. The man must be a quick and methodical worker because such inspections usually have to take place on a Sunday, when such parts may be made "dead," and only a few hours for the work are allowable.

Most of the modern automatic rotary convertor equipments are provided with mechanical means for starting up, etc., in case the automatic features fail or be out of commission, so that it is incumbent upon the engineer-in-charge to see that both the attendants and inspectors start up a machine by hand, say, once per week and make themselves thoroughly familiar with this method of operation.

Much valuable time is thereby saved when a failure of the automatic operations occurs, because the procedure merely resolves itself into ordinary routine work and no time is lost in restoring the supply. It is very seldom, however, that such a thing happens.

The high-tension automatic oil switches are subjected to very heavy work and are put to a far greater strain than is the case of those located in manually-operated sub-stations and should be inspected very frequently, therefore.

Large contactors, in the same way, require periodic inspection.

The preceding points in the organization of automatic sub-stations apply both to automatic rectifier and rotary equipment, but a few additional details about the former may be of interest.

With the glass bulb type of rectifier, the bulbs require very careful and delicate handling. Heavy handling and constant tilting for starting up will decrease their useful life by a considerable amount.

To obviate this trouble, the constant dropping out and starting up of bulbs, the excitation current should be maintained at the correct value, and accurate readings taken of such values as are obtained when the bulb keeps on dropping out, before the current is increased, and the date when such an alteration was made. Details of the correct excitation currents for all sizes of bulbs are given on page 1397.

The resultant figures, taken at different periods, will give an indication (quite a rough one, certainly) as to how far a bulb has advanced in its useful life, and how much more work may reasonably be expected.

A chart embracing all sub-stations, with the number of every bulb in each sub-station (as shown in Fig. 55), is convenient for quick reference. It shows at a glance the most expensive sub-station from a bulb replacement

SCHEDULE OF BULBS LIGHTING (THREE-WIRE SYSTEM)

	1 −			1 +			1A −			1A +		
Name of sub-station	Bulb No.	Date of failure	Life	Bulb No.	Date of failure	Life	Bulb No.	Date of failure	Life	Bulb No.	Date of failure	Life

FIG. 55. BULB RECORD CHART

point of view. Thus, steps may be taken to ascertain the causes of these failures.

Black and white framed schematic drawings, portraying the general scheme of the automatic equipment in the form of single line diagrams, must be hung in each sub-station in order that reference may be made at any time should occasion demand. It is impossible to carry in the mind every detail of automatic wiring when many different types of sub-stations are installed, so that reference to these diagrams is essential.

Each sub-station should be supplied with a log book in which all visitants enter up load conditions, particulars of switching operations and details of trouble, also machine loads and voltages at the sub-station end, together with those at the controlling sub-station end.

Another log book kept at the main sub-station where the junior engineer is stationed, containing particulars of mains linking and switching operations, whether temporary or permanent, is very necessary and should be kept up to date. Attendants in manually-operated sub-stations containing supervisory apparatus for controlling automatic sub-stations, should enter up load and voltage readings at half-hour intervals during the day and hourly intervals during the night, together with particulars of operations, on a special sheet, provided for that purpose. This sheet to be sent in daily.

The keys of all sub-station main doors should be kept in a cabinet provided for that purpose at this main sub-station, and contractors' men or persons of other departments requiring any set of keys should sign for same, and, when returned, a responsible junior engineer will append his initials showing that they have been received. In this way " lost " keys are easily traced.

In addition to the above, as in manually-operated

sub-stations, an ambulance box complete with bandages, iodine, etc., must be kept in a prominent position; also instructions for dealing with electric shock, Workmen's Compensation Act, Electricity Regulations, Factory Act extracts, etc., must be prominently displayed. A pigeon hole receptacle hanging on the wall allows of the grouping of small spares neatly and prevents loss and damage.

A van or lorry at the disposal of the automatic sub-stations is desirable for the periodical transport of stores, renewal parts, etc., which have to be made up from time to time.

Paraffin hurricane lamps should always be kept in readiness for instant use in case of a total failure of the supply, also anti-fire appliances, spare fuses, etc.

Earth circuit breakers and resistances to limit the "earth" leakage current, to, say, 30 amp., in the case of small rectifier stations, and to, say, 100 amp. in the case of large automatic rotary convertor sub-stations, should be erected in each substation, together with a recording ammeter, so that any particular part of the system may be earthed separately. It has been found a good plan to link through solid all the neutrals of a system of automatic sub-stations and to earth them at a manually-operated sub-station, where any leakage is noticed and is reported immediately by the attendant-in-charge. On such an occasion the mains department find it convenient to separate the sub-stations and to close the earth breaker in such sub-stations, i.e. they split up the network in order to locate the fault.

When any trouble occurs which seems likely to affect consumers, the mains department should be informed, and they should proceed to the source of trouble.

Their services may not be required, but on the other hand, much delay and inconvenience is prevented if they are on the spot ready for all emergencies, for it

may be necessary to throw over some load on to another distribution, in order to restore the sub-station to normal and to carry out a small repair to a unit, which necessitates shutting down the faulty part.

The junior engineers or inspectors should be capable of dealing with any of the minor troubles that arise, and should be in a position to advise and help the attendants in their respective " areas."

Where a very great number of such sub-stations is operating it is a good plan to have a junior engineer standing by at a central sub-station, where a telephone exchange permits him to keep in touch with the whole job, giving advice and instructions during the 3 p.m. to 11 p.m. shift. This post should be filled by competent engineers, as it entails a great amount of responsibility.

This person is especially valuable after office hours. He knows the sub-stations under his control and their method of linking up through the outside network, the fusing points, conditions of load and general performance.

In the event of trouble he should issue such instructions to the attendants as will cause the least possible delay in restoring a sub-station or plant to normal, and, if necessary, should proceed to the site, if from the attendant's report he deems the situation serious enough for his personal supervision. Of course, if the nature of the trouble is very serious, he should send for one of the senior engineers.

Each sub-station has a complement of recording instruments, such as recording voltmeter and ammeter, per machine, and in the case of traction sub-stations, earth leakage, rail point drop, gas main to track potential difference, etc., in addition to those previously mentioned.

It is strongly recommended, therefore, where many such recorders are in service, that a man, competent to

attend to all minor troubles, visit all sub-stations and keep the instruments in good working order. The attendants, of course, see that they are inking properly, clocks are going and keeping good time, etc. The importance of a correct and accurate record of performance is readily appreciated and often gives valuable information on mysterious happenings which otherwise would never be solved in the ordinary way.

They also give hints of approaching trouble which may thus be investigated and corrected before a breakdown occurs.

An emergency kit of tools should be kept available at a convenient and accessible place, so that a fitter is able to collect them and carry on with repair work without loss of time. This, especially, is important during the night hours, when a man is called out. The vehicle which fetches him can load up his tools at a central place, instead of having to make a journey of several miles, perhaps, to collect the necessary tools before work can proceed.

Junior engineers, inspectors, and attendants should send in written reports weekly, the salient points of which are entered up in log books under the appropriate sub-station heading, routine work being noted by the engineer-in-charge. The sheets should then be filed for future reference.

Insulation tests taken, say, weekly, are important, but if numerous sub-stations are involved where running conditions permit such tests to be taken only over the week-end, it is sufficient to take a combined test. A detailed test is advisable if possible, as then one is perfectly certain that all brushes are freed in their boxes when the armature test is taken.

If the resultant combined reading is low, further tests on each individual part of the plant should be taken in order to locate the part which is giving the low reading,

Date..

AUTOMATIC SUB-STATIONS

ATTENDANT'S SPECIAL REPORT
TO
SUB-STATIONS ENGINEER

Time received call.................. *To*..........................*Sub-station.*

Sub-station at which Call was received.................................

Particulars of Trouble

TIME OF ARRIVAL	
LOAD CONDITIONS, ETC.	
REGULATOR STOP NO. (IF ANY)	
TIME MAINS DEPT. SENT FOR	
TIME MAINS DEPT. ARRIVED	
TIME STATION NORMAL AGAIN	
LOAD CONDITIONS (NORMAL)	
FAULTY PARTS DESCRIBED	

Nature of trouble and theory as to why it occurred—

Signature......................................

THIS REPORT MUST BE SENT IN BEFORE LEAVING

FIG. 56. SPECIAL REPORT SHEET

when steps must be taken to find out and rectify the trouble.

In addition, wattmeter readings, feeder breaker cyclometer readings, line leakage tests, etc., should be taken and logged in special books kept for that purpose.

Cyclometer readings should be logged every time the sub-station is visited, so that the time when a circuit breaker operates is narrowed down to a few hours, i.e. between two consecutive visits, and the number of consecutive operations also may be determined.

It has been found an advantage to have printed special report sheets distributed, to be used in the event of a serious breakdown or failure of supply. These convey special information to the engineer-in-charge, as it is often impossible to obtain such facts when a breakdown has occurred during the evening or night, and the man or men concerned are off duty and cannot, therefore, be interrogated. These are filed under the first letter, in alphabetical order of the appropriate sub-stations; the information is entered up briefly in the log books, thus forming a check and providing details of interest in the plant history.

Fig. 56 shows such a special report sheet.

Peak load readings taken at all substations several times during a year will serve to show how the load and distribution are growing. The figures, compared with readings taken at corresponding times in previous years, will give an indication where additional plant is required to meet the growing demand.

Curves, plotted with month-of-year and maximum-demand in kilowatts as abscissae, will yield at a glance such information.

Attendants should be supplied with bicycles for their quick conveyance from place to place, so that they may be entirely independent of public conveyances, and thus much loss of time may be eliminated.

SECTION XXII

AUTOMATIC SUB-STATIONS

BY

C. J. SARJEANT

SECTION XXII

AUTOMATIC SUB-STATIONS

FIFTEEN years or so ago the idea of running electrical machines in isolated sub-stations behind locked doors, without the usual staff of attendants, was viewed with a certain amount of distrust, but to-day the necsssary control devices have been perfected and automatic control equipments have thereby reached a high standard of reliability. Some hundreds of automatically controlled sub-stations have been in satisfactory operation for a number of years.

The automatic control apparatus not only performs all the operations of switching, starting up and shutting down the machines—operations usually performed by skilled attendants—but performs these operations more efficiently and with greater reliability than is possible with a manually-operated sub-station, as the uncertainty of the human element is absent. In addition, it provides full protection to the plant at all times, and every contingency is provided for, with nothing left to the guesswork or judgment of an operator.

The reliability and efficiency of the automatically controlled station depend, however, on the control gear being as simple as possible, together with reliable protective apparatus to guard against all possible faults.

There is a great tendency in certain cases for the purchaser to ask for all kinds of extra apparatus which is entirely unnecessary. This only complicates the whole control scheme, and very often leads to more trouble than if it had been left out.

On the other hand, it is essential that the purchaser before buying the equipment should satisfy himself that

the equipment will perform the duties required of it, and that it is fully protected. Another tendency which should be avoided as much as possible is that of putting a number of units in one sub-station.

The automatically controlled sub-station to be economical and simple should not, except under special circumstances, have more than two units installed in it.

It is very doubtful whether sub-stations having three or more units in them are run more economically without attendants. Even if they are economical, the reliability is not of such a high standard, owing to the extra complication necessary to control a number of machines in one sub-station.

APPLICATION

Generally speaking, the field for the automatic sub-stations is where it is desired to boost up the voltage of a distribution network at various points, the voltage at which would otherwise have to be raised by installing more plant in the main sub-stations and running very much heavier feeders, because the cost of running a manually-operated sub-station for this purpose would be prohibitive.

From this it will be seen that their general application is as booster sub-stations in the fringe of a large power and lighting system, or at points on a suburban traction system which will not become particularly heavy load centres.

They may also be very economically applied to mining and industrial enterprises, as it is not then necessary to employ a special staff to run the plant and the maintenance can be done by the staff already employed in maintaining the rest of the electrical equipment.

A further very economical application is to main line railway electrification, where the line passes through long stretches of sparsely populated country, where if

manually-operated substations were used they would necessitate the building of accommodation for the staff and also carrying all supplies for their maintenance.

There are other applications, such as underground sub-stations, where the difficulty of ventilation would affect the health of the operators, or sub-stations situated in unhealthy climates.

A very sound application to generating stations as apart from sub-stations is that of small hydro-electric stations. There are a great many places where a relatively small amount of water power is available which could not be used economically if a staff had to be employed to run the station, but if run unattended would justify the expense of installing the plant to feed into the main system.

In other cases the water supply for small stations can be stored up in a dam during the light load periods, the load of which can be carried by the main station. When the peak loads come on these small stations can then be started up to help the main station.

ADVANTAGES

Before installing an automatically controlled sub-station, naturally the first thing to be considered is what advantages it has over the manually-operated station.

There are many advantages and these vary in importance, depending upon the local conditions peculiar to each installation.

Cost of Running the Plant. The main economy in the cost of running the plant is the saving of the operators' wages, particularly where it is necessary to run three shifts of two men per shift.

It can generally be shown that the extra capital cost of the automatically controlled single unit sub-station has been more than saved on the wages bill in 18 months

or two years. As there is no resident staff, there is a considerable saving in light and fuel.

Cost of Distribution. Since the wages bill is practically eliminated, it at once becomes possible to decentralize the units and locate single units at their natural load centre, thus considerably reducing the size of the feeders, and so enabling a large saving to be made.

In many cases it will be found that the saving in the cost of the feeder copper more than offsets the extra cost of the automatic gear.

Line Pressure. Once it has become possible to economically decentralize the units and so connect them at a greater number of points in the network, it immediately becomes obvious that the line pressure will be more uniform as the voltage drop between the feed points is reduced.

Location. A sub-station may be located in any convenient position, having regard to its natural load centre.

This may effect very large savings on main line electrification, where the line passes through sparsely populated country, as in many cases it would be necessary to build housing accommodation for the staff, and also arrange to transport all the necessities of life.

Sub-stations may be located underground in positions where, while the ventilation is satisfactory for machines, the air may not be of such a nature that attendants could live in it without affecting their health.

Protection. A well-designed automatic control equipment provides protection against all abnormal conditions at all times, and entirely eliminates the possibility of abuse due to careless operation. No such claim can be made for the manually-operated station, where it is possible for the attendant to cause serious damage by incorrect switching.

Outage. It is not generally realized that there is a great reduction in the duration of a supply failure when automatic reclosing devices are installed.

It is quite common practice to leave transformer and distribution stations locked up without any attendant and without automatic reclosing devices. If a breaker opens for any reason it is necessary to send an operator along to reclose it. In many cases the electricity suppliers are not aware that the breaker has opened until a complaint is made, which means a long delay before the circuit is again restored, with corresponding annoyance to consumers.

Labour. In many countries the type of labour available is neither skilled nor reliable enough to take charge of electrical machinery, and imported labour would be far too costly. In this case automatically controlled substations can be very economically installed, as it is then only necessary to have a few skilled men for maintenance.

The automatically controlled sub-station has also great advantages in the times of industrial strife, as it will continue to run providing the incoming supply is available.

TYPE OF PLANT

Automatic control can be applied to almost every type of converting and transforming plant, to hydro-electric generating stations, and to both alternating and direct current distribution systems.

The types of converting plant to which it has already been applied are as follows—

Rotary convertors, motor convertors, synchronous motor-generator sets, induction motor-generator sets, and mercury arc rectifiers, both of the sealed bulb and steel tank type.

Other types of plant to which it has been applied are—

Synchronous condensers, hydro-electric stations, transformers, balancers, battery charging sets, etc.

It is not proposed to go into the method of operation of all the various types, but at a later stage the complete scheme of operation and protection of the more usual rotary convertor sub-stations will be described in detail. It will then be seen that by modifying the starting sequence to suit another type of machine, it can just as easily be controlled automatically.

The transformer sub-station presents far less difficulties than those containing rotary plant, as there is no complicated starting sequence. Switching on and off the transformer units by one or other of the methods of starting and stopping described later, can be easily accomplished. With the more recent development of changing the taps on a transformer while it is on load, the voltage of the system can be kept constant automatically, if desired.

CONTROL SUPPLY

The supply for operating the various control and protective devices should be as reliable as possible.

The most reliable source of all is the incoming supply to the unit to be controlled, and as the unit is useless without it, there is no object in having a control supply available if the main supply has failed.

It is usual, therefore, to install a control transformer connected to the high-tension incoming supply through fuses and isolating links, which transformer steps the voltage down to a value suitable for operating the control devices.

If it is essential to have a direct current supply for the control devices, it is usual to install a small motor generator set for this purpose, the motor being driven from the control transformer mentioned above.

The control supply for the outgoing feeders should

be taken from the busbar to which the feeders are connected.

Batteries for the control supply should be avoided if possible owing to the amount of maintenance required and the cost, as, in addition to the cost of the battery, provision has to be made for charging same.

Batteries should only be used where the incoming alternating current supply is of such a high voltage that a control transformer and its protective gear would be too costly. It will then be found cheaper to install a battery to supply the current to operate the high-tension switchgear and to use the lower voltage usually obtainable after the high-tension switch has been closed to charge the battery.

In this case the battery should be automatically charged in order to keep it in condition so that it will be ready at all times to perform its function.

METHOD OF STARTING AND STOPPING

There are several methods of starting the machines in automatic sub-stations, and the particular method used must be decided upon only after due consideration has been given of the particular system to which the machine is to supply power.

The following are the usual methods used—

1. Start up when the load demand reaches a predetermined value as indicated by the busbar voltage and measured by a contact-making voltmeter, and shut down by an underload relay when the load has fallen to a predetermined value.
2. By a time switch.
3. By a manually-operated remote control switch.
4. By a control switch located in the sub-station.
5. By supervisory control.
6. By closing a high-tension feeder switch at the power station or some other point.

7. By a float switch (hydro-electric installations).

The above methods of starting all have their particular applications as shown below.

1. By Load Demand. This method of control has the advantage that the machine is always ready to start when there is a load for it to carry, and will shut down when the load has fallen off, without human aid. It is particularly suitable for power and lighting systems or tramway systems where the normal load is taken by the manually-operated sub-stations, but the voltage of the system is maintained, during the peak loads, by the automatic sub-stations.

Normally, the peak loads come on at particular times of the day, but climatic conditions or other reasons may cause the peak load to come on at any time, and by this method the machines will always start when required and shut down when the load falls off.

The starting impulse is given by a contact-making voltmeter connected to the system so as to measure the voltage. At a predetermined low voltage it will operate to start the machine.

A time delay relay should always be used in conjunction with the contact making voltmeter to prevent starting the machine due to voltage fluctuations of short duration.

The stopping impulse is given by an underload relay. This relay measures the load on the machine and when it has fallen to a pre-determined low value, at which it would not be economical to keep the machine running, it operates to shut down the machine.

Here, again, a time delay relay should be used in conjunction with the underload relay to prevent stopping the machine due to load fluctuations of short duration.

2. Time Switch. This method of starting and stopping is used where it is necessary to run the machine

for a definite period in a day and it is known that it will not be required at other times.

As an example a machine may be installed on a tramway system, where it is always necessary to have it running as long as the tram service is in operation, but this service may only be between certain hours such as 5 a.m. until 11 p.m.

Requirements such as these are well suited to time switch control.

3. Manually-operated Remote Control Switch. This method is used where it is desirable to be able to start and stop the machine at any time, under any conditions of load, and is usually employed on suburban railways.

In this case, it is usually preferable to have the power available during the rush hours rather than delay the starting of the machines until after the peak load has come on, so as to be able to get the trains away as quickly as possible. The machines are, therefore, started up some little time before the peak load comes on.

A contact-making voltmeter is not suitable for this class of sub-station because the longer trains run during the rush hours would when passing over certain sections of the line cause a drop in the voltage of the section for a time sufficient to start the sub-station. The load would drop off again as soon as the train got off the particular section, with the result that the machine in the sub-station would be continually starting and stopping, also the train's speed would fall during the time which must necessarily elapse between the starting impulse and the connecting of the machine to the bars.

4. Manually-operated Control Switch Located Inside the Sub-station. The particular application of this method of starting and stopping is where the machine

to be controlled is situated on the spot where the power is actually required such as would be the case in factories or mines where conversions are made to suit their requirements.

In this case the sub-station equipment would be under the care of the maintenance engineer, who would start and stop the machine at the required times.

Once having been started, the maintenance engineer can leave it to take care of itself while he carries out his other duties, knowing that any temporary fault will only cause a temporary shut down, as, once the fault has cleared, the machine will automatically start up and go back on to the busbars.

5. Supervisory Control. This method of control is used where it is desired to control a number of switching operations in one or more sub-stations from one control point. If ordinary remote control switches were used, this would entail using a great many pilots, some of which might have to be of considerable size, owing to the currents taken by the usual control apparatus, and the limits set by voltage drop over the long distance between the apparatus to be controlled and the controlling station.

There are several types of this apparatus which closely resemble automatic telephone and traffic control equipment, and the number of pilots used varies from three to six, depending upon the type.

If the loading of the sub-stations to be controlled is known, it is possible to use this scheme without installing any meters at the remote control point, but if it is not known meters should be installed so that the power units can be connected to the system as and when required.

By this means a large number of switching operations can be controlled and indicated, and it is not necessary for them all to be located in one sub-station.

6. Closing a High-tension Feeder Switch at Some Remote Point. This scheme can only be used where a high-tension feeder supplies power to the machine in the sub-station and nothing else.

By this means it is possible to start the machine by energizing the feeder, and stop it by de-energizing the feeder, thus obtaining remote control without the use of pilots.

7. Float Switch. This scheme is sometimes used in hydro-electric stations where it is required that the machine feeds into the system at all times, providing there is a sufficient quantity of water available for driving the turbine.

By this method the turbine is started when a certain head of water is available, and shut down when the head falls to a predetermined low figure.

DOUBLE UNIT SUB-STATIONS

The second unit in a double unit sub-station may be started by any of the following methods—

1. Load Demand. As the voltage of the system will be held up by the first machine, the second machine cannot be started up by a contact-making voltmeter. As the load on the system increases, the first machine, by maintaining the voltage, becomes overloaded.

It is, therefore, necessary to start the second machine by a contact-making ammeter which measures the load on the first.

At a predetermined load on the first, the contact-making ammeter operates to start the second.

A time delay relay should be used in conjunction with the starting relay to prevent the second machine starting up due to load fluctuations on the first, of short duration.

To shut down the second machine the contact-making

ammeter should operate another set of contacts when the total load of the sub-station has fallen to a value which can be carried by the first machine. Here, again, it should work in conjunction with a time delay relay to prevent shutting down the second machine due to a temporary falling off of the load.

2. Time Switch. This method can only be used if it is known that the load on the first machine will exceed a definite value at a definite time, and so is very limited in its application.

3. Manually-operated Remote Control Switch. This method should only be used where a meter is provided at the remote control point, so that the operator can start the second machine when the load exceeds the capacity of the first, or, in the case where it is known at what times the load will be too great for one machine such as on a railway system where the train schedule is known.

4. Supervisory Control. As in the case of the manually-operated remote control switch, this scheme should only be used providing a meter is installed at the remote control point or the loading of the system is such that the load can be previously predetermined.

If there is no means of knowing what the load on the first unit is, there is a danger of overheating it and thus disconnecting it from the busbars at the time it is most urgently needed.

5. Temperature of First Unit. A method sometimes used is to start up the second unit when the load on the first has caused the latter to reach a predetermined temperature, as indicated by a thermal relay. This relay should not be confused with the protective thermal relay used to protect the machines from overheating due to continued overloads, and should be set to operate at a lower temperature than the protective relay. This method of starting the second unit enables

full advantage to be taken of the overload capacity of the machine.

In this case the thermal relay is used to shut the second machine down when the temperature of the first machine has dropped so that it can again take the total load of the station.

General. When more than one unit is installed in one sub-station the control connections should be so arranged that the order of starting the machines can be periodically changed, so as to equalize wear.

It is desirable, when the machines are started by an automatic device inside the sub-station, that some provision be made to start the second unit if the first fails to be connected to the busbars after the starting impulse has been given.

This is not necessary where the starting is done by a remote control switch or supervisory gear, as in these cases indication will be given as to whether the machine has started or not, and if not the other can be started.

In some cases it is desirable to have a combination of the methods of starting and stopping, but this is not usually necessary, and as the reliability depends also on simplicity, it is undesirable to unnecessarily complicate the equipment.

As an instance of where it is essential to combine the load demand method of starting with a time switch, the following example is given.

An automatic sub-station is installed on a tramway system to boost the voltage of a certain section during peak loads and is started by a contact-making voltmeter.

Between the hours, say, of 12 midnight and 4 a.m., the direct current tramway system is completely shut down, but the alternating current system is alive at all times to provide lighting.

When all the trams are in their sheds all the manually-operated stations are shut down. As the last machine is taken off the bars the voltage of the system drops to zero.

The contact-making voltmeter in the automatic sub-station immediately indicates low voltage, and after the time setting of the time delay relay has expired the machine starts up and goes on to the bars.

Since there is no load for it to pick up, the underload relay gives the stopping impulse and after a time delay the machine shuts down.

This starting and stopping will go on during the whole time the direct current system is supposed to be dead and, of course, besides being dangerous to any men repairing the trolley, is very wasteful and results in unnecessary wear.

To overcome this difficulty a time switch should be used to allow the contact-making voltmeter to have control during the working hours only.

COMPLETE DESCRIPTION OF THE OPERATION AND PROTECTION OF A TYPICAL DOUBLE UNIT TRAMWAY SUB-STATION

The number of types of automatic control gear and number of methods of starting only one type of machine, such as the rotary convertor, are so numerous that space does not allow of them all being described in detail. Furthermore, once a particular type is thoroughly understood the difference in the types of control gear and the application of the gear to the various types of machines will be readily understood.

The following is a complete description of the operation of a two-unit automatic rotary convertor sub-station for a tramway system, the rotaries being

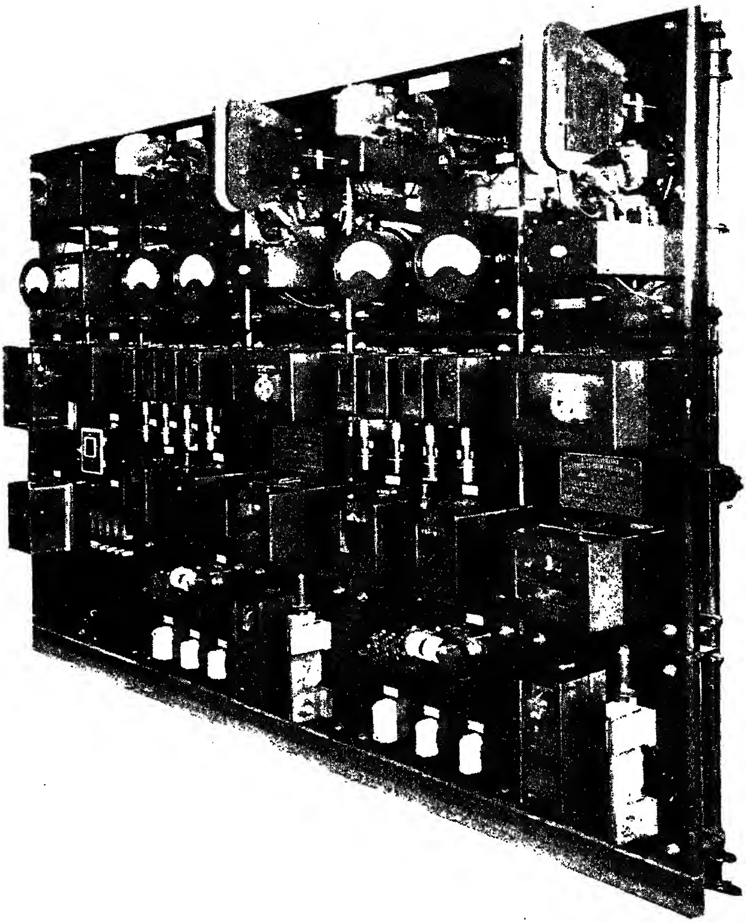


FIG. 1. DIRECT CURRENT AND RELAY PANELS FOR TWO 400 KW ROTARY CONVERTORS

compound wound and started by a starting motor connected to the main transformer in series with the rotary armature during the starting sequence.

The complete equipment for controlling the machine (except the high-tension oil circuit breaker equipment) is illustrated by Figs. 1 and 2. The key diagram (Fig. 3) shows the complete connections of one unit, the connections of the apparatus common to both units, and the interconnections between the units. In this diagram the various contacts, operating coils, etc., are grouped in their respective electrical circuits, irrespective of their relative physical position, so as to enable the circuits to be easily followed.

Each device is given a number which is used throughout this description and also appears on the diagram.

Accompanying the diagram is a list of the devices, their numbers, and the number of the coils and contacts of the device.

The object of showing the coils and contacts in this way is that when a coil has been energized, reference to the list shows at once how many contacts have been operated, and they can then be found on the diagram and their function noted.

The sequence of operation is given in tabular form, so that it can be easily followed.

The first column gives the sequence step by step, the second column gives the effect of each operation, while the third column states which particular contact on opening or closing performs the operation, together with any special remarks necessary.

Detailed Description of Scheme of Control.

Operation of First Unit to Start

In the following description it is assumed that the various isolating switches are closed, the control

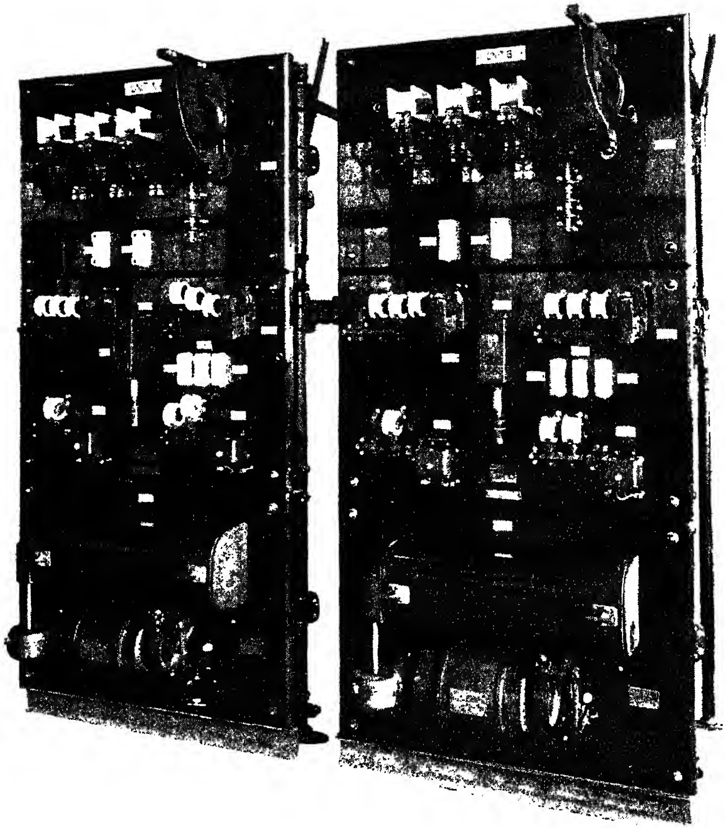


FIG. 2. STARTING PANELS FOR TWO 400 KW 550 VOLTS DIRECT CURRENT TWO-WIRE ROTARY CONVERTORS

transformers energized, and that all protective devices have their contacts in the normal position.

Sequence of operation	Effect	Remarks
1 Master starting element (1) closes its contacts	Completes the coil circuit of A.C. under-voltage relay (27)	Contacts Nos. 74–75 now closed; see A.C. control connections
2 A.C. under-voltage relay (27) opens its contacts	Interrupts the short-circuit across the coil of single-phase starting protective relay (32)	Contacts Nos. 1–37 now opened; see A.C. main connections
3 Single-phase starting protective relay (32) operates	(*a*) Completes the coil circuit of master control contactor (5)	Contacts Nos. 35–46 now closed; see A.C. control connections
	(*b*) Completes coil circuit of auxiliary starting relay (1*x*)	Contacts Nos. 35–46 now closed. This relay starts the second unit if the first fails to start
4 Master control contactor (5) closes	(*a*) Maintains its own coil circuit and connects finger No. 11 to A.C. control bus	Contacts Nos. 1–2 now closed; see A.C. control connections
	(*b*) Prepares circuit for D.C. operated control devices	Contacts Nos. 89–100 now closed; see D.C. control connections
	(*c*) Completes circuit of low-voltage release (7LVR) on oil circuit breaker (7)	Contacts Nos. 1–2 now closed; see A.C. control connections
	(*d*) Completes the coil circuit of brake solenoid (34*x*)	Contacts Nos. 13–60 now closed; see A.C. control connections
5 Magnet of solenoid brake (34*x*) closes	Lifts the brake to release motor (34*y*); completes circuit of motor (34*y*)	Contacts Nos. 35–70 now closed; see A.C. control connections
6 Motor (34*y*) starts	Rotates master controller (34)	

As the master controller rotates, the various segments come into contact with their fingers and fix the subsequent operations.

	Sequence of operation	Effect	Remarks
7	(*a*) Segment No. 4 makes contact with its finger	Energizes sequence timing relay (48)	See A.C. control connections. Relay (48) now timing
	(*b*) Segment No 12 makes contact with its finger	Completes the coil circuit of motor-generator contactor (6)	See A.C. control connections
8	Motor-generator contactor (6) closes its contacts	Connects motor of motor-generator set to L.T. side of control transformer (11)	See A.C. main connections
9	Motor-generator set accelerates and generator builds up its voltage	Energizes coil circuit of synchronous field contactor (31)	See generator connections
10	Synchronous field contactor (31) closes its contacts	(*a*) Connects auxiliary field of rotary to generator	Contacts Nos. 101–105 now closed; see generator connections
		(*b*) Connects in circuit the fixed tapping of main field rheostat	Contacts Nos. B–L now closed; see main shunt field connections
11	(*a*) Segment No. 2 leaves its fingers		Prevents master control contactor (5) from reclosing (once it has been opened) unless master controller (34) has returned to the off position
	(*b*) Segment No. 3 leaves its finger	Interrupts coil circuit of auxiliary time delay starting relay ($1x$)	Prevents the starting of the second unit
12	Segment No. 8 makes contact with its finger	Completes the closing coil of auxiliary relay ($7x$)	See A.C. control connections
13	Auxiliary relay ($7x$) closes its contacts	(*a*) Completes the circuit of motor ($7y$)	Contacts Nos. 66–67 now closed; see A.C. control connections
		(*b*) Prepares the circuit of its own retaining coil	Contacts Nos. 65–67 now closed; see A.C. control connections
14	Motor ($7y$) rotates	Operates the closing mechanism of oil circuit breaker (7)	
15	Oil circuit breaker (7) closes	(*a*) Connects the H.T. side of main power transformer to the A.C. busbars	
		(*b*) Prepares a circuit for holding coil of negative high-speed circuit breaker (54)	Contacts Nos. 18–94 now closed; see D.C. control connections

	Sequence of operation	Effect	Remarks
16	Starting motor starts	Rotates armature of rotary convertor	
	Synchronous speed indicating relay (13) plunger rises, due to voltage across starting motor windings	Bridges first gap in segment No. 13, through segment No. 9, which makes contact with its finger	Contacts Nos. 13–9 now closed; see A.C. control connections. The purpose of this gap is to stop the sequence if synchronous speed indicating relay (13) does not function properly
18	Segment No. 8 leaves its finger		The function of this segment has already been completed
19	Segment No. 10 makes contact with its finger	Prepares an alternative path bridging second gap in segment No. 13	See A.C. control connections
20	Segment No. 13 leaves its finger	Interrupts the coil circuit of the brake solenoid ($34x$)	See A.C. control connections
21	Magnet of solenoid brake ($34x$) opens	Interrupts the circuit of, and applies the brake to motor ($34y$)	Contacts Nos. 35–70 now opened; see A.C control connections
22	Motor	Master controller (34) stops, waiting for machine to synchronize	

The rotary approaches synchronism with correct field adjustment, the auxiliary field having fixed the polarity at which the rotary builds up its voltage.

	Sequence of operation	Effect	Remarks
23	D.C. Polarized relay (36) operates	Prepares an alternative retaining circuit for coil of master control contactor (5)	Contacts Nos. 47–48 now closed; see A.C. control connections
24	Rotary synchronizes	Voltage across the starting motor falls off, with the result that synchronous speed indicating relay (13) operates	See A.C. main connections
25	Synchronous speed indicating relay (13) plunger falls after a time interval	Bridges second gap in segment No. 13, thus completing the circuit of brake solenoid ($34x$)	See A.C. control connections

Sequence of operation	Effect	Remarks
26 Magnet of solenoid brake (34x) closes	Lifts the brake to release motor (34y); completes the circuit of motor (34y) by closing an interlock	Contacts Nos. 35–70 now closed; see A.C. control connections
27 Motor (34y) starts	Rotates cylinder of master controller (34)	
28 Segment No. 13 makes contact with its finger	Takes over retaining circuit of brake solenoid (34x)	
29 Segments Nos. 15 and 16 make contact with their fingers	Complete the coil circuit of running contactor (16)	See A.C. main connections
30 Running contactor (16) closes	(a) Connects the rotary direct to low-tension side of main power transformer	Starting motor is now short-circuited; see A.C. main connections
	(b) Completes the coil circuit of field contactor (14)	Contacts Nos. 89–90 now closed; see D.C. control connections
	(c) Interrupts an alternative circuit for coil of master control contactor (5)	Contacts Nos. 47–48 now open; see A.C. control connections. The polarity of the convertor is checked at this point
	(d) Completes the coil circuit of equalizer contactor (22)	Contacts Nos. 89–91 now closed; see D.C. control connections
31 (a) Field contactor (14) closes	(a) Connects in circuit the moving arm of the main field rheostat	Contacts "L–R" now closed; see D.C. main connections
	(b) Interrupts the coil circuit of synchronous field contactor (31)	Contacts Nos. 101–102 now open; see generator connections
(b) Equalizer contactor (22) closes	(a) Connects series field windings to equalizer busbar	See D.C. main connections
	(b) Prepares the circuit for D.C. operated devices	Contacts Nos. 100–17 now closed; see D.C. control connections
32 Synchronous field contactor (31) opens	(a) Disconnects auxiliary field of rotary from the auxiliary generator	Contacts Nos. 101–105 now opened; see D.C. generator connections
	(b) Interrupts the circuit of the fixed tapping on field rheostat	Contacts "L–B" now opened; see D.C. main connections

	Sequence of operation	Effect	Remarks
33	Segment No. 12 leaves its finger	Interrupts the coil circuit of motor-generator contactor (6)	See A.C. control connections
34	Motor-generator contactor (6) opens	Disconnects motor of motor-generator set from control transformer (11)	See control transformer connections. The motor-generator set, having performed its function, comes to rest
35	Segments Nos. 17 and 18 make contact with their fingers	(*a*) Complete the circuit of the holding coil of high-speed circuit breaker (54)	See D.C. control connections
		(*b*) Complete the coil circuit of auxiliary time delay relay (54*y*)	See D.C. control connections
		(*c*) Complete the coil circuit of auxiliary time delay relay (54*z*)	See D.C. control connections. Relay (54*z*) now timing
		(*d*) Complete the coil circuit of repeat action relay (66)	See D.C. control connections. Relay (66) advances one notch
36	(*a*) Auxiliary time delay relay (54*y*) closes its contacts	Short-circuits the resistance in series with the holding coil of the high-speed circuit breaker (54)	Contacts Nos. 93–94 now closed; see D.C. control connections
	(*b*) Auxiliary time delay relay (54*z*) closes its contacts after a time interval	Completes the coil circuit of reset contactor (54*x*)	Contacts Nos. 94–96 now closed; see D.C. control connections
37	Reset contactor (54*x*)	Completes the circuit of the closing coil of high-speed circuit breaker (54)	Contacts Nos. 84–88 now closed; see D.C. control connections
38	Closing mechanism and interlocks of high-speed circuit breaker (54) operate	(*a*) Short-circuit the coil of reset contactor (54*x*)	Contacts Nos. 84–95 now closed; see D.C control connections
		(*b*) Complete the coil circuit of positive line breaker (18)	Contacts Nos. 92–18 now closed; see D.C. control connections
		(*c*) Interrupt the coil circuits of auxiliary relay (54*y*) and time delay relay (54*z*)	Contacts Nos. 98–18 now opened; see D.C. control connections. Relay (54*y*) now timing
		(*d*) Interrupt the coil circuit of repeat action relay (66)	Contacts Nos. 98–18 now opened; see D.C. control connections. Relay (66) reclaims the notch taken during the starting period

	Sequence of operation	Effect	Remarks
	(*a*) Reset contactor (54*x*) opens	Interrupts the circuit of the closing coil of high-speed circuit breaker (54)	Contacts Nos. 84–88 now opened; see D.C. control connections
	(*b*) Positive line breaker (18) closes	(*a*) Connects rotary to positive D.C. busbar	
		(*b*) Interrupts the circuit of sequence timing relay (48)	Contacts Nos. 4–59 now opened; see A.C. control connections. Relay (48), now de-energized, ceases timing
	(*c*) Auxiliary relay (54*z*) opens	Interrupts the coil circuit of reset contactor (54*x*)	Contacts Nos. 94–96 now open; see D.C. control connections
40	Closing mechanism of negative high-speed circuit breaker (54) drops back	Allows the main contacts to come together, thereby short-circuiting the load limiting resistance and connecting the machine direct to the negative busbar	See D.C. main connections
41	Auxiliary relay (54*y*) opens, after a time delay	Inserts a resistance in series with the holding coil of high-speed circuit breaker (54), thereby reducing the holding coil current to normal	Contacts Nos. 93–94 now opened; see D.C. control connections

The rotary convertor is now connected to the direct current busbars and picks up load.

	Sequence of operation	Effect	Remarks
42	Segment No. 13 leaves its finger	Interrupts the coil circuit of brake solenoid (34*x*)	See A.C. Control connections
43	Magnet of solenoid brake (34*x*) opens	Interrupts the circuit of, and applies the brake to, motor (34*y*)	Contacts Nos. 35–70 now open; see A.C. control connections
44	Motor (34*y*) stops	Master controller (34) comes to rest in running position	

The rotary continues to run until shut down by the time clock, or, alternatively, it is shut down by the operation of one or more of the protective devices.

Shutting Down on Cessation of Demand for Power

Sequence of operation	Effect	Remarks
1 Master starting element (1) (time clock) opens its contacts at predetermined time	Interrupts the coil circuit of A.C. under-voltage relay (27)	Contacts Nos. 74–75 now open; see A.C. control connections
2 A.C. under-voltage relay (27) operates	Short-circuits the coil circuit of single-phase starting protective relay (32)	Contacts Nos. 1–37 now closed; see control transformer connections
3 Single-phase starting protective relay (32) opens its contacts	Interrupts coil circuit of master control contactor (5)	Contacts Nos. 35–46 now opened; see A.C. control connections
4 Master control contactor (5) opens	(*a*) Interrupts circuit of holding coil of high-speed circuit breaker (54)	Contacts Nos. 89–100 now opened; see D.C. control connections
	(*b*) Interrupts the coil circuit of line breaker (18)	Contacts Nos. 89–100 now opened; see D.C. control connections
	(*c*) Interrupts the circuit of low-voltage release (*7lvr*) on oil circuit breaker (7)	Contacts Nos. 1–2 now opened; see A.C. control connections
	(*d*) Interrupts the coil circuit of running contactor (16)	Contacts Nos. 16–40 now open; see A.C. main connections
	(*e*) Completes the circuit of brake solenoid (*34x*)	Contacts Nos. 60–4 now closed; see A.C. control connections
(*a*) High-speed circuit breaker (54) opens	Inserts load-limiting resistance in negative side of rotary	See D.C. main connections
(*b*) Line breaker (18) opens	Disconnects rotary from positive D.C. busbar	See D.C. main connections
(*c*) Oil circuit breaker (7) opens	Disconnects the main power transformer from the A.C. supply	See A.C. main connections

Sequence of operation	Effect	Remarks
(*d*) Running contactor (16) opens	(*a*) Removes the short-circuit from the starting motor ready for the next start	See A.C. main connections
	(*b*) Interrupts the coil circuit of field contactor (14)	Contacts Nos. 89–90 now opened; see D.C. control connections. Field contactor (14) opens
	(*c*) Interrupts the coil circuit of equalizer contactor (22)	Contacts Nos. 89–91 now opened; see D.C. control connections. Equalizer contactor (22) opens
(*e*) Magnet of solenoid brake (34*x*) closes	Lifts the brake to release motor (34*y*); completes the circuit of motor (34*y*)	Contacts Nos. 35–70 now closed; see A.C. control connections
Motor (34*y*) starts	Rotates cylinder of master controller (34)	Cylinder moves towards off position
Segment No. 4 leaves its finger	Interrupts the circuit of brake solenoid (34*x*)	
Magnet of solenoid (34*x*) opens	Interrupts the circuit of and applies the brake to motor (34*y*)	Contacts Nos. 35–70 now open; see A.C. control connections
Motor (34*y*) stops	Master controller (34) comes to rest in off position	

All other control devices now assume their normal position corresponding to rotary at rest, and the equipment is ready to restart whenever there is a demand for power as determined by master-starting element (1).

Protective and Fault Indicating Devices

The operation of the equipment under overload or short-circuit conditions is given in detail in order that the automatic reclosing sequence may be thoroughly understood, but the manner in which the other devices

operate, commencing on page 1510, is more briefly described, as their functions are more easily understood.

High-speed Circuit-breaker (54).

Sequence of operation	Effect	Remarks
1 Heavy overload or short-circuit occurs on D.C. system	D.C. current rises beyond setting of negative high-speed circuit breaker (54)	
2 High - speed circuit breaker (54) opens	(*a*) Inserts load limiting resistance in negative circuit	Limits the current to a value within the commutating capacity of the machine
	(*b*) Interrupts the coil circuit of positive line breaker (18)	Contacts Nos. 92–18 now opened; see D.C. control connections
	(*c*) Completes the coil circuit of auxiliary relays (54*y*) and (54*z*)	Contacts Nos. 98–18 now closed: see D.C. control connections. Auxiliary relay (54*z*) now timing
	(*d*) Completes the coil circuit of repeat action relay (66)	Contacts Nos. 98–18 now closed; see D.C. control connections. Relay (66) advances one notch
3 (*a*) Line breaker (18) opens	(*a*) Disconnects the rotary from positive D.C. busbar	
	(*b*) Completes circuit of sequence timing relay (48)	Contacts Nos. 59–4 now closed; see A.C. control connections. Relay (48) now timing
(*b*) Auxiliary relay (54*y*) closes	Over-excites the holding coil of high-speed circuit breaker (54)	Contacts Nos. 93–94 now closed; see D.C. connections

NOTE. The time between the opening of the high-speed circuit breaker (54) and the line breaker (18), during which a limited current is allowed to flow, allows the overload relay on the feeder time to operate. If the high-speed circuit breaker opened the circuit direct the overload relay on the feeder would not have time to operate.

	Sequence of operation	Effect	Remarks
4	Auxiliary relay (54*z*) operates (after a time delay)	Completes the coil circuit of reset contactor (54*x*)	Contacts Nos. 94–96 now closed ; see D.C. control connections
	Reset contactor (54*x*) closes	Completes the circuit of the closing coil of high - speed circuit breaker (54)	Contacts Nos. 88–84 now closed ; see D.C. main connections
6	Closing mechanism and interlocks on high - speed circuit breaker (54) operate	(*a*) Short-circuit the coil of reset contactor (54*x*)	Contacts Nos. 84–95 now closed ; see D.C. control connections
		(*b*) Complete the coil circuit of line breaker (18)	Contacts Nos. 92–18 now closed ; see D.C. control connections
		(*c*) Interrupt the coil circuits of auxiliary relay (54*y*) and time delay relay (54*z*)	Contacts Nos. 93–18 now opened ; see D.C. control connections. Relay (54*y*) now timing
		(*d*) Interrupt the coil circuits of repeat action relay (66)	Contacts Nos. 98–18 now opened ; see D.C. control connections. Relay (66) now timing ; notch taken will, in time, be reclaimed if fault has been cleared
	(*a*) Reset contactor (54*x*) opens	Interrupts the circuit of the closing coil of high - speed circuit breaker (54)	Contacts Nos. 88–84 now opened ; see D.C. main connections
	(*b*) Positive line breaker (18) closes	(*a*) Connects rotary to positive D.C. busbar	
		(*b*) Interrupts the circuit of sequence timing relay (48)	Contacts Nos. 59–4 now opened ; see A.C. control connections. Relay (48) now de-energized, ceases timing
	(*c*) Auxiliary relay (54*z*) opens	Interrupts the coil circuit of reset contactor (54*x*)	Contacts Nos. 94–96 now opened ; see D.C. control connections
	Closing mechanism of negative high-speed circuit breaker (54) drops back	Allows the main contacts to come together thereby short-circuiting the load limiting resistance and connecting the machine direct to the negative busbar	See D.C. main connections
9	Auxiliary relay (54*y*) opens after a time delay	Inserts a resistance in series with the holding coil of high-speed circuit breaker (54) thereby reducing the holding coil current to normal	Contacts Nos. 93–94 now opened ; see D.C. control connections

If the fault has been cleared, the negative high-speed circuit breaker (54) remains closed and the rotary convertor continues to supply power. If the fault remains, the breakers will again open, and the reclosing sequence described above will be repeated. If the breakers are opened a predetermined number of times within a given period, repeat action relay (66) finally opens its contacts and interrupts the coil circuit of master control contactor (5) thus shutting down the equipment until the fault has been cleared and repeat action relay (66) reset manually.

OPERATION OF OTHER PROTECTIVE DEVICES

Overspeed Device (12). Should the rotary convertor attain an excessive speed the overspeed device (12) will operate and interrupt the coil circuit of master control contactor (5).

The equipment will then be shut down and locked out until the overspeed device has been reset manually.

Alternating Current Under-voltage Relay (27). *Starting Up.* Should the voltage of the alternating current high-tension supply fall below a predetermined value, the equipment is prevented from starting by the under-voltage relay (27), which prevents single-phase starting protective relay (32) from closing and thus holds open the coil circuit of master control contactor (5).

Running. Should the voltage of the alternating current high-tension supply fall below a predetermined value when running, the equipment is shut down by under-voltage relay (27), which opens the single-phase starting protective relay (32) which, in turn, interrupts the coil circuit of master control contactor (5), thus shutting down the machine until normal conditions prevail.

Alternating Current Overload and Earth Leakage Relay (28). This relay (connected to current transformer energized by the incoming alternating current supply) when it operates, trips oil circuit-breaker (7) and, at the same time, opens the coil circuit of master control contactor (5), thus shutting down and locking out the equipment until the relay is manually reset.

Single-phase Starting Protective Relay (32). The alternating current under-voltage relay (27) and single-phase protective relay (32) are connected across different phases of the incoming alternating current lines ; thus, unless all three phases are energized, the coil circuit of master control contactor (5) is not completed. It is by this means that protection is obtained from single-phase starting.

Polarized Relay (36). If due to any cause, the polarity of the rotary be reversed, polarized relay (36) operates and interrupts the coil circuit of master control contactor (5) thus shutting down the equipment.

Since the contacts of the polarized relay are bridged by an interlocking contact on the running contactor (16), the equipment will restart if conditions require it, the polarity being corrected during the starting sequence by the field flashing motor-generator set.

Starting Motor Temperature Relay (37). Should the starting motor overheat, due to too frequent starting or failure of the rotary convertor to synchronize properly, the starting motor temperature relay (37) operates and interrupts the coil circuit of master control contactor (5), thus shutting down and locking out the equipment until the relay is manually reset.

Bearing Temperature Relay (38). Each of the machine bearings is furnished with a temperature relay (38) which, whenever the bearings become overheated, operates, and interrupts the coil circuit of master control

contactor (5), thus shutting down and locking out the equipment until the relay is manually reset.

Sequence Timing Relay (48). Should the starting sequence not be completed within a given time (the positive line breaker (18) remaining open), relay (48) will complete its timing stroke and operate, thus interrupting the coil circuit of master control contactor (5), thereby shutting down and locking out the equipment until the relay is manually reset.

Machine Temperature Relay (49). This relay possesses heating and cooling characteristics similar to the machine it protects. The relay operates to shut down the equipment when a predetermined temperature has been attained.

When the temperature has fallen sufficiently to allow the machine to be put back into service, the equipment will automatically restart if the load conditions on the direct current system are such as to warrant this.

Reverse Power Relay (56). Any tendency of the rotary convertor to run inverted is prevented by the reverse power element of this relay which, when it operates, interrupts the coil circuit of master control contactor (5). This relay is self-resetting and allows the rotary convertor to restart when necessary.

Direct Current Earth Leakage Relay (64). Should an earth occur on the machine, due to a flash-over or failure of insulation, this relay will operate and interrupt the coil circuit of master control contactor (5), thus shutting down and locking out the equipment until the relay is manually reset.

OPERATION OF SECOND UNIT TO START

Normal Starting. Under normal operating conditions the first unit to start will be running on load, and when this load exceeds a pre-determined value for which the master starting element (1*a*) is set, this device

operates and closes its contacts (Nos. 81–1), thus completing the circuit of time delay starting relay (2*a*). This relay provides a time delay between the operations of the master starting element (1*a*) and the starting up of the rotary, to prevent starting due to momentary fluctuations of the load. At the end of the timing period, time delay starting relay (2*a*) closes its contacts (Nos. 78-77) which complete the coil circuit of the alternating current under-voltage relay (27) of the second unit.

When this relay (27) operates the remainder of the sequence is the same as described for the first unit to start, with the following addition, that when the master control contactor (5) closes, it bridges the contacts (Nos. 78–77) of the time delay starting relay (2*a*) by its contacts (Nos. 79–77) to prevent shutting down the unit immediately when the load falls off the station and the master starting element (1*a*) de-energizes relay (2*a*).

Shutting Down. When both units are running the second unit to be started up will shut down when the total load on the sub-station falls below the value at which the master starting relay (1*a*) is set. Thus, when the load falls off, relay (1*a*) opens contacts (Nos. 81–1) and closes contacts (Nos. 80–1), thereby energizing the time delay stopping relay (3*a*).

This relay provides a time delay between the operation of relay (1*a*) and the shutting down of the rotary to prevent shutting down due to momentary fluctuations of the load.

At the end of the timing period relay (3*a*) operates and opens its contacts (Nos. 77–76) thus de-energizing the coil circuit of the alternating current under-voltage relay (27), and shutting down the unit as previously described for the first unit.

Emergency Starting and Stopping. If the first unit fails to start or is shut down by one of the protective

devices, the motor-driven master controller (34) will either fail to move from its off position or after the operation of a protective device will rotate to the off and stop there.

This will cause the emergency time delay starting relay ($1x$) to operate, after a short time interval, to close its contacts (Nos. 76–78) and bridge the contacts of the time delay starting and stopping relays ($2a$) and ($3a$) respectively, thus completing the coil circuit of the alternating current under-voltage relay (27) of the second unit, causing it to operate and start the second unit. The second unit will then continue to run until the master starting element (1) (time clock) operates to open its contacts and de-energize the coil circuit of the alternating current under-voltage relay (27) of the first unit. Relay (27) causes the single-phase starting protective relay (32) of the first unit to open its contacts and interrupt the coil circuit of the emergency time delay starting relay ($1x$) which in turn opens its contacts, interrupting the coil circuit of alternating current under-voltage relay (27) of the second unit which shuts down in the normal way as previously described.

Order of Starting the Units. The order of starting the units may be changed at will to equalize the wear on the machines by the change-over switch (9) provided for this purpose.

If the change-over switch (9) is closed in its top contacts unit *A* will start first, followed by unit *B*.

If switch (9) is closed in its bottom contacts unit *B* will start first followed by unit *A*.

Whether unit *A* or *B* is appointed to start first, the other unit will start if the first fails.

SCHEMES OF OPERATION

In the previous pages the scheme using the controller to obtain the sequence was described, but the

sequence can be equally well obtained without it, by using a greater number of interlocking contacts and relays.

Having described fully the scheme for connecting a motor-started compound wound rotary convertor on to the busbars at a fixed voltage, now consider the scheme where a motor-started shunt-wound rotary convertor having an automatic voltage regulator is used.

As far as starting up, synchronizing and getting the machine ready to be closed on to the direct current busbars, the sequence is the same. After this, as the machine has to be equipped with a motor-operated field rheostat or some other device to enable the voltage regulating relay to keep the voltage at the desired value, use of this is usually employed to parallel the machine on to the busbars.

The usual procedure is that when the machine is running from the alternating current end, the field rheostat is rotated to the "all-in" position (i.e. minimum volts). A voltage equalizing relay then takes control of the motor-operated field rheostat and operates it to raise the voltage of the machine until it is equal to, or just above that of the system to which the machine is to be connected. The voltage equalizing relay then operates and causes the direct current circuit breakers to close and connect the machine to the system. As soon as this is done the control of the rheostat is transferred from the voltage equalizing relay to the voltage regulating relay, which maintains the voltage at the desired value. On some equipments a load regulating relay is also used to take control from the voltage regulating relay if the load exceeds a predetermined figure, and lower the station voltage so as to throw some of the load on to adjacent sub-stations.

With this type of control, if the direct current circuit

breakers operate due to overload, it is usual to automatically reduce the voltage of the machine to a minimum and then equalize it to that of the system before reclosing the breakers.

Tap-started Rotary Convertors. The sequence of operations for this type of machine differs from the motor-started machines in the method by which it is started from the alternating current end, but once running from this end, the sequence of closing the direct current side will follow the scheme used for the motor-started rotary, depending upon the type of regulation.

On tap-started machines, particularly those of large capacity, it is necessary to raise the direct current brushes from the commutator before starting, to prevent sparking. It is, therefore, necessary to fit a motor-operated brush-raising device to the machine. This device must be so interlocked with the equipment that it is impossible to start the machine until the brushes are raised, and after it has been started and synchronized, it must be impossible to close the direct current circuit breakers until the brushes are again lowered on to the commutator.

When the brushes are raised off the commutator it is necessary to leave a pair of brushes (one on a positive brush arm and the other on a negative brush arm) on the commutator in order to connect the synchronizing and polarity relays across the armature.

One method of starting this type of machine is briefly as follows—

1. If the direct current brushes are not already raised off the commutator when the sequence commences they will be automatically raised before it is possible to start the machines.

2. The high-tension oil switch closes to energize the rotary transformer.

3. The rotary slip rings are connected to the taps

on the transformer, the field circuit being open and split into sections to guard against high induced voltages.

4. The rotary now starts rotating and runs up to synchronous speed.

5. Synchronism is indicated by a synchronous speed indicating relay connected across the direct current armature, this relay being of the type which will not operate on an alternating current. As the rotary accelerates the current at the direct current brushes is alternating, but when the machine is in synchronism it becomes uni-directional and thus causes the relay to operate.

6. The field winding is next separately excited for a short period from a separate source of supply such as an exciter or battery which fixes the polarity of the rotary.

7. The rotary is then changed over from separate excitation to self-excitation.

8. The slip rings are then disconnected from the starting taps of the transformer and immediately after connected to the full voltage.

9. The motor-operated brush-raising device now comes into operation to lower the direct current brushes on to the commutator.

10. The machine is now running from the alternating current end, ready to be connected to the direct current busbars, as previously described. As an extra safeguard a polarized relay checks the polarity and prevents further operation if this should be wrong.

A second method of starting this type of machine is briefly as follows—

1. If the direct current brushes are not raised off the commutator when the sequence commences, they will be automatically raised before it is possible to start the machine.

2. The high-tension oil switch closes to energize the rotary convertor transformer.

3. The rotary slip rings are connected to the taps on the transformer, the field being connected through a reversing contactor for normal self-excitation.

4. The convertor now starts rotating and runs up to synchronous speed.

5. A polarized motor relay is connected across the direct current armature, the field of this motor being a permanent magnet. Until the convertor is in synchronism the current in the armature of the polarized relay is alternating, which merely causes the motor to oscillate, but when the convertor is in synchronism, direct current is delivered to the armature of the relay causing it to rotate in a direction depending upon the polarity of the convertor.

6. If the polarity of the convertor is correct, the motor will rotate in one direction and operate one set of contacts to allow starting sequence to continue, but if incorrect it will rotate in the opposite direction and operate another set of contacts. These latter contacts operate the field reversing contactor, thus reversing the field connections. This causes a reverse field current which quickly reduces the field and convertor voltage to zero. As the voltage falls through zero, the field contactor operates and again restores the field connections to normal. The field having been biased in the right direction, the convertor builds up with the right polarity.

7. The rotary being in synchronism with the correct polarity causes the polarized relay to rotate, and by means of its contacts it causes the slip rings to be disconnected from the starting taps on the transformer and immediately afterwards connected to the full voltage.

8. The motor-operated brush-raising device now

comes into operation to lower the direct current brushes on to the commutator.

9. The machine is now running from the alternating current end, ready to be connected to the direct current busbars, as previously described.

PROTECTION OF MACHINES

There are two classes of faults to be catered for as follows—

(*a*) Those which are only of a temporary nature, so that the machine may be put back into service as soon as conditions have again returned to normal.

Under this class are the following—

1. Overloads and short circuits on the direct current system which are only of a temporary nature.
2. Overheating of the machine.
3. Reverse power.
4. Low voltage of the incoming supply.
5. Wrong polarity.

(*b*) Those which are of a permanent nature or which may have caused damage to the machine, thus making it necessary to examine the machine and its equipment before allowing it to be put back into commission.

Under this class are the following—

1. Overspeed.
2. Alternating current overload or short circuit.
3. Alternating current earth leakage.
4. Direct current earth leakage.
5. Failure of the equipment to start up and connect the machine to the system.
6. Overheating of the starting motor (if any).
7. Direct current overloads or short circuits of a persistent nature.
8. Overheating of the bearings.

There are certain other faults to be protected against depending upon the system and type of machine.

As an example, if the alternating current distribution system from which the machine takes its supply consists of underground three-core cable, then there is no need to include protection against starting or running with a phase open, because if a fault develops in the cable it at once becomes a short between phases or a fault to earth, and immediately operates the overload or earth leakage protective relays, which, in turn, open the oil circuit breaker which disconnects the supply to the sub-station.

On the other hand, if the system is of the overhead type having each phase run separately on the poles, it may be possible for a break to occur in one phase which would not cause a short circuit or leakage to earth, and so to prevent injury to the machine it is necessary to include protective devices, both to prevent the machine starting (if shut down) and also to shut it down if running.

As an example, where extra protection is needed due to the type of machine, consider the rotary convertor.

The rotary convertor may be started from the alternating current end by two methods: (*a*) By a starting motor; (*b*) by taps on the main transformer.

When started by a starting motor it is necessary to keep the field circuit closed, and allow the field to build up as the synchronizing of the machine depends upon the correct field strength being obtained. If the field were open circuited the machine would not synchronize, and so the starting sequence would be held up.

From the above it will be seen that it is not necessary to provide any further protection against failure of the field. On the other hand, when using the tap started method it is necessary to provide some means of flashing or reversing the field to establish correct polarity, which necessitates opening the field circuit.

It then becomes necessary before putting the machine

on to the bars, to ensure that the field contactor has closed and the field built up.

To check this a relay whose coil is connected in series with the field to measure the field current is provided.

This relay is of no use to protect against loss of field once the machine is on the bars, because in the case of an open circuit it would not operate quickly enough, and in the case of the more usual fault, i.e. shorted turns in a field spool, it would not operate at all.

The reverse power relay provides protection against faults in the field circuit, because as soon as a fault develops in the field circuit the voltage of the machine falls and causes the main current to reverse.

The methods of protecting against the faults detailed above are fully dealt with on previous pages, except that of protecting against direct current overloads and short circuits, for which there are many types of protection which will now be considered.

DIRECT CURRENT OVERLOADS AND SHORT-CIRCUIT PROTECTION

When considering the direct current protection on the machine, this must always be carefully considered in conjunction with the direct current feeder protection, if any, and also the system which the machine is required to feed into, i.e. whether traction, lighting, or power.

Traction Systems. On modern traction systems, to enable the heavy peak loads to be dealt with, the machines should be capable of withstanding, for a short time, loads up to three or three-and-a-half times their full load rating, which means that for economical design the loads are approaching the safe commutating capacity of the machines. Consequently, if the load

exceeds this value it should be disconnected as quickly as possible.

Furthermore, in automatic sub-stations it is essential that after a heavy fault, which is not uncommon, the machine still be in perfect condition so that it can be reconnected to the system without inspection and cleaning, which would necessitate locking the machine out of commission every time a fault occurs.

The ordinary switchboard type of circuit breaker, besides not being mechanically suited for operating during long periods without any attention, has not sufficient speed of opening to prevent damage being done to the commutator or brushgear.

The scheme using an overload relay operating to open the coil circuit of a contactor, while being mechanically sound, is too slow.

To obtain a sound mechanical device, together with very rapid operation on fault, the high-speed circuit breaker has been developed, one form of which is fully described on pages 1538 to 1547. With this type of breaker it has been found in actual practice that after the machine has been subjected to some 50 to 60 dead short circuits, it can be put back into commission without any cleaning up.

This is not the case with any other type of protection and so it becomes essential that a high-speed circuit breaker be used. Once it is decided to use high-speed breakers for protection it becomes necessary to consider in what part of the circuit they are to be connected.

Generally speaking, the high-speed circuit breaker should be connected in the feeder circuits, and not in the machine circuit. The reason for this is obvious if the relative speeds of operation of the high-speed circuit breaker and other forms of protection are studied. The high-speed circuit breaker operates from five to ten times as fast as other devices and so, if connected

in series with them, will always open and clear the fault before they have time to operate. Thus, if a machine protected by a high-speed breaker is supplying load to a number of feeders protected by overload relays and contactors, any fault of sufficient capacity to trip the high-speed breaker will cause it to open, leaving the faulty feeder breaker still closed as well as interrupting the supply to the remaining sound feeders; Whereas, if the protection was reversed, the faulty feeder only would open, leaving the machine connected to the busbars to supply the sound feeders.

In some instances, where the number of feeders is large and the capacity small, it becomes too expensive to install high-speed circuit breakers in each feeder, and then it is necessary to use them on the machines only.

It then becomes necessary to ensure that the faulty feeder breaker opens even though the high-speed circuit breaker on the machine opens first.

One method of doing this is as follows—

A high-speed circuit breaker is connected in the negative of the machine, and across the main contacts of the breaker is connected a limiting resistance. A contactor is connected in the positive side of the machine to completely disconnect it from the positive busbar, and the coil of this contactor is controlled by an auxiliary switch on the high-speed circuit breaker, so that when the breaker opens it first of all limits the current passing through the machine to within the commutating capacity, and afterwards disconnects the machine from the positive busbar by interrupting the coil circuit of the contactor which opens. The reason for completely disconnecting the machine on fault and not only inserting the limiting resistance is that a very short time rated resistance is used to prevent its being too bulky and expensive. This type of protection on

the machine ensures that the overload relay in the feeder has time to operate before the current is finally interrupted.

The overload relay on the feeder circuit is of the latch type which, on the occurrence of a fault, latches itself in the tripped position. Thus, once it has operated, even though the fault has been cleared by the machine protective devices, it remains open, de-energizing the coil circuit of the feeder contactor, which ultimately opens.

If the overload relay were of the self-resetting type there is a possibility of its resetting when the machine has been disconnected, before the feeder contactor has had time to operate.

The overload relay is fitted with an electrical reset device, so that the latch may be reset when desired by the operation of a reclosing relay.

A second method of doing this is to protect the feeder circuit by a relay which operates only on rate of rise of current, together with an overload relay to take care of normal overloads. The relay operating on the rate of rise of the fault current should be designed so that once it has operated it is maintained in this position until the feeder breaker has opened. This can either be done by a latch mechanism, which would have to be fitted with an electrical reset device, or by a retaining coil. This scheme would probably be satisfactory without the limiting resistance across the high-speed circuit breaker contacts and the positive contactor on certain systems, but on other systems where the inductance of the system in series with the fault keeps down the rate of rise, it would probably still be necessary to retain these features.

As an instance of when it is essential to connect high-speed circuit breakers in the machine circuit the following is an example—

A sub-station contains several machines, but only one outgoing feeder breaker. During light loads only one machine is required, but during peak loads several are required in parallel. The feeder breaker is set to trip at some value slightly above the maximum peak load, which is far beyond the capacity of one machine, and it is therefore no protection when only one machine is running. The only place to connect the high-speed circuit breaker to fully protect the machines in this case is to connect one in each machine circuit.

If the high-speed circuit breaker is of the polarized type, i.e. that it will only trip with current flowing in one direction, such as that described on pages 1506–1508, the very best arrangement for the protection of machines and feeders is as follows—

In each feeder circuit there should be provided a high-speed circuit breaker connected up to trip due to external faults, i.e. forward current.

A high-speed circuit breaker should be connected in the positive lead of the machine, connected up to trip when the current reverses, and an ordinary slow-speed breaker should be connected in the negative lead, this breaker being set at a high value for forward current.

With this arrangement all faults external to the sub-station, the current of which is in a forward direction, would cause the feeder high-speed breaker only to operate; the machine high-speed circuit breaker, being connected for reverse tripping, cannot operate, and the slow-speed breaker would not have time to operate.

Now consider a fault occurring on the machine such as an earth on the positive brush.

This would cause the current to flow as follows—

(*a*) From adjacent sub-stations through the feeder breakers in the reverse direction, thus they would not open; through the machine high-speed circuit breaker

in the reverse direction, thus causing it to open and disconnect the fault from the direct current system without interrupting the feeder circuit.

(*b*) From the second machine in the same sub-station (if any) running in parallel, through its slow-speed breaker, through its high-speed circuit breaker in a forward direction so that it will not trip, through the high-speed circuit breaker of the faulty machine in the reverse direction, which breaker disconnects the faulty machine from the positive busbar. The slow-speed circuit breaker on the sound machine has not time to operate, thus it leaves the sound machine connected to the busbar.

(*c*) From the negative (earth) through the slow-speed circuit breaker of the faulty machine, through the machine itself, and back to earth through the fault, thus causing the breaker to open.

The particular function of this breaker is to interrupt the fault circuit around the machine during the time the machine is slowing down. Even though the supply is disconnected from the machine, the inertia of heavy machines causes them to run for some time during which the voltage is maintained and the fault current persists until the speed dies down.

It is realized that the slow-speed circuit breaker connected in the negative is an extra refinement, but the above combination gives as near 100 per cent protection as it is possible to find.

Some manufacturers favour the use of load limiting resistances connected in series with the machine, which resistances are cut out in two or three steps when the machine is first put on to the bars, providing the load is not beyond a certain predetermined figure and re-inserted when a definite value of overload has been reached.

These resistances, to be of any use at all, have to

be rated to carry their current for some few minutes, otherwise the thermal relay protecting them will constantly be operating and disconnecting the machine from the busbar. The machine then has to remain disconnected until the resistance has again cooled. If they are so rated they become bulky and expensive. They are also very wasteful.

With the high standard of perfection reached on the present-day machines and protective gear the use, except in very special circumstances, of these resistances has become unnecessary.

There is a number of automatic sub-stations which have now been running for years without them, and have proved perfectly satisfactory.

Lighting Systems. On these systems it has been found from experience that the ordinary overload relay and contactor type of protection is all that is necessary, as in this case heavy faults are so few and far between that the extra cost of the high-speed circuit breaker is not warranted.

Power Systems. On these systems the type of protection depends on the loading of the system. If the load consists of small plant spread over a large area, then the protection used for lighting system could be safely used, as the chance of very heavy faults is remote, but if, on the other hand, a large concentrated load is supplied, the fault current may be very large and it would probably pay to install high-speed circuit breaker protection.

MULTI-UNIT AUTOMATIC SUB-STATIONS

The automatic sub-station to be reliable should be as simple as possible, and the simplest scheme of all is the single-unit sub-station.

The procedure of adding more and more units in the one sub-station to cater for increasing load, as has been

the practice for manually-operated sub-stations, is not economical. A new sub-station should be put down as near the new load centre as possible in preference to having to run two machines in parallel in the same sub-station.

Two-unit sub-stations are very often necessary, so that, while one unit is out of commission for maintenance purposes, the other will run when required, to supply the load. Depending upon the position of the sub-stations in relation to the load on the system, it may be found that it is not necessary to install a stand-by unit in every sub-station, as in many cases it will be found possible to run both units in an adjacent sub-station to supply the load while the single-unit sub-station is out of commission.

The addition of a third unit adds very much to the complication of the control gear, as explained later.

It should be clearly understood that there is no reason why the two units should not run in parallel occasionally when required, as might be the case with a traction system, where, due to race meetings or the like causing a heavy peak load, there is the necessity for extra plant to deal with the load.

One of the most essential features in multi-unit sub-stations is that if any fault develops on one of the machines, or its equipment, it should in no way prevent the other or others from operating satisfactorily, but, on the contrary, should be the means of starting another machine to take its place.

Another very necessary feature is that the order of starting the machines can be changed from time to time to even the wear on the machines and their equipments.

These features can be very simply accomplished in two-unit sub-stations, but when three or more units are installed in one sub-station the scheme becomes very

complicated and the complications necessarily mean that the equipment is not so reliable.

The one exception, where the number of units does not cause any complication, is the case of remote controlled equipments, when the machines are connected to the busbars at a fixed voltage (i.e. have no automatic voltage regulation). In this instance, the order of starting the machines is entirely under the control of the operator in the remote control room, and no interconnections are required to make the machines share the load and so each machine and its equipment is independent of the others.

FULLY AUTOMATIC DOUBLE-UNIT SUB-STATIONS

One machine will obtain its starting impulse from a contact-making voltmeter connected to the busbars which, when the voltage of the system falls indicating load, operates its contact to start the machine.

The other machine will start due to one or other of the following causes—

(*a*) The load becoming too heavy for the first machine, this condition being indicated by a contact-making ammeter, or

(*b*) The first machine failing to be connected to the busbars, as indicated by an emergency starting relay.

(*c*) The first machine being disconnected from the busbars due to a fault.

A multi-blade double-throw switch is provided so that the order of starting the machines can be changed periodically. When closed into one set of contacts, one machine will be controlled by the contact-making voltmeter and the other by the contact-making ammeter and emergency starting relay. When thrown to the other contacts the sequence of starting is reversed.

If the machines have no automatic voltage regulator then no further interconnections are required, but if

fitted with automatic voltage regulators it is necessary to ensure these operating together so that the load is shared between the units.

It is not possible to have a voltage regulating relay on each equipment to control the regulator, as they could not be guaranteed to operate at exactly the same value, so it becomes necessary to use one regulating relay only when more than one unit is running.

When only one unit is running at a time this can be accomplished either by installing only one relay in the sub-station and transferring its controlling contacts automatically from one equipment to another, depending upon which is running, or by installing a relay on each equipment. When both units are running in parallel, if the regulators are of the motor-operated type such as field rheostats or induction regulators, it is not satisfactory to control each one independently from the voltage regulating relay, as they could not be guaranteed to operate at the same speed, and this would cause the load to be shared unequally and may result in reversing the current of one machine and thus shutting it down.

Mechanically coupling the regulators, while ensuring that they each travel the same amount, will not cause the load to be shared equally unless the characteristics of the machines and transformers are exactly the same, and even if satisfactory in this respect, should be avoided if possible, as a complete failure of the sub-station will be caused by a fault on one regulator.

One method of overcoming this difficulty is to control the regulator of one machine by the voltage regulating relay, thus keeping the voltage of the station at the desired value while the regulator of the machine running in parallel is controlled by a differential balanced current relay, one coil of which is connected in the circuit of each machine.

As the voltage regulating relay varies the position of the regulator on the machine, an unbalancing of the loads on the two machines results. This unbalancing causes the differential relay to operate the regulator on the other machine to restore the balance.

This scheme necessitates a certain number of control interconnections between the two equipments, as the differential relay has to be cut out of operation if either of the units is running by itself. It should be possible to completely isolate the one unit from the other for maintenance and repairs and so multi-blade isolating switches will have to be provided.

FULLY AUTOMATIC TRIPLE-UNIT SUB-STATIONS

The difficulties in designing automatic sub-stations containing three or more units do not seem to be appreciated by operating engineers, so it is proposed to go very briefly into these.

The essential features of a triple-unit sub-station are as follows, and it would not be satisfactory if any were omitted—

1. Each unit must be capable of running by itself.
2. Each pair of units must be capable of running satisfactorily in parallel.
3. All three must be capable of running satisfactorily in parallel.
4. A fault on any one unit must not affect the running of the other two, either singly or in parallel.
5. It must be possible to completely isolate one unit and all its equipment from the other two, leaving these units connected so that they may run singly or in parallel, for maintenance and repairs.
6. The first unit to start when the voltage of the system drops, the second when the load on the first is above a predetermined value, and the third when

the load on the two running is above a predetermined value, and to shut down as the load again falls off.

7. If either the first or second unit fails to start when required, or develops a fault when running, the third unit should automatically take its place.

8. The order of starting to be changed from time to time, to even the wear and tear on the machines and their equipments.

From the above requirements, without going into details it will be readily seen that the complete scheme for the sub-station becomes very complicated, a great deal of extra apparatus has to be installed and a great many interconnections of the control circuits have to be made, resulting in high first cost, less reliability, and greater difficulty in locating faults, with the result that the equipments are out of commission for longer periods.

Nevertheless, there are certain cases where it is necessary to install triple-unit sub-stations, and a number of such are working satisfactorily.

AUTOMATIC RECLOSING DIRECT CURRENT FEEDERS

Automatic reclosing direct current feeders may be fitted with any of the following types of overload protection—

1. High-speed circuit breaker.

If this breaker is of the type which will trip at a definite value of current irrespective of the rate of rise, then no further protection is necessary, but if of the type which only operates on a high rate of rise of current, then it is necessary to include an overload relay to interrupt the holding coil of the breaker when a slowly rising overload occurs.

As mentioned previously, this type of protection is specially suitable for traction feeders.

2. Overload relay with contactor which is held closed electrically.

This type of protection is slow in operation and should therefore only be used on lighting systems or small tramway feeders where the faults are infrequent or limited by the resistance of the feeder.

3. Induction or impulse relay with contactor which is held closed electrically.

This relay is connected across the secondary of a current transformer (or the equivalent) the primary of which is connected in series with the feeder breaker. On the occurrence of a fault giving a high rate of rise of current, a voltage is induced in the relay coil to operate the relay.

The claim for this type of protection is that it discriminates between faults which cause a rapidly rising current and legitimate overloads such as the starting currents of motors, for which the rate of rise of current is relatively low. On the other hand, provision should be made for disconnecting a fault giving a slow rate of rise of current. To give protection against this type of fault it is necessary to provide the ordinary type of over-current relay in addition.

4. Overload and/or inductive relay with latched type contactor.

The latched type contactor has been developed to obtain a cheaper type of device than the high-speed circuit breaker, but one which will open very much quicker than the contactor which is held closed electrically.

The latched mechanism is far more robust than that of the ordinary switchboard type circuit breaker and, therefore, is suitable for operating a large number of times without requiring any attention. It is speedier in operation than the electrically-held contactor, as the tripping relays operate direct on the latch and there

is no lag in opening while the flux is dying down. Once opened it is quicker in rupturing the arc than the switchboard type of breaker because it is fitted with magnetic blow-out and arc chutes. The same arguments for and against the inductive relay hold good in this case as described previously.

There are various schemes available for reclosing the breaker after it has opened due to a fault and these schemes may be used in conjunction with any of the types of protection mentioned above.

Repeat Action Scheme. This scheme is so named because it repeats the action of reclosing the feeder breaker on to a fault a number of times before locking it out of commission.

The operation of the relay which performs this function is as follows—

When the relay is energized, the plunger rises and causes the notching-pawl to turn the notching wheel one notch, and at the same time lifts the time-lag device. The release-pawl, operated by the time-lag device, prevents the wheel from slipping back.

If, while on this notch, the relay is de-energized, the plunger will drop instantaneously—and free of the time-lag device, which by the means of the release-pawl, will hold this notch to the end of the time setting. If the relay does not operate again within the pre-arranged time, the time-lag device will free this pawl and allow the notching wheel to return to its original position. But if the relay does operate, the plunger again rises and restarts the notching operation until the pre-determined notch is reached; and then a pin on the notching wheel causes the toggle mechanism to operate the contacts and so lock out the breaker.

This scheme offers the automatic equivalent to the usual procedure in a manually-operated substation in that, if a fault occurs, attempts are made to burn it

out. Should the attempts fail, the feeder is locked out of commission pending investigation and so remains until the fault is cleared, after which the relays are reset manually or by pilot control from the control point. The chief advantage of this scheme is that once the feeder breaker has been locked out the line is dead, and the removal of the fault can be accomplished without danger. This feature is of great importance in the case of traction systems, where sometimes the fault may be due to the presence of some object in contact with the live rail.

Faults and Overloads. When an overload or short-circuit occurs the feeder breaker opens and, by means of an auxiliary switch, energizes the coil of the repeat action relay, which operates and advances one notch of the notching wheel. After a short time delay a reclosing relay causes the breaker to reclose. On the breaker reclosing, the coil of the repeat action is de-energized, but the notch already taken is held for a short time by a time delay mechanism. Should the breaker remain closed for a period at least equal to the time setting, the notch is reclaimed, but if the fault persists the breaker again opens and the relay takes a further notch.

This operation of reclosing and opening will continue until the fault has cleared or the repeat action relay has advanced to the last notch for which it is set. The relay will then lock out and prevent the breaker from being closed until after the fault has been cleared and the relay reset.

When this scheme is employed in conjunction with a machine equipment which also incorporates a repeat action relay in its protective gear, it is usual to set the feeder relay with one notch less than the machine relay, so that if a heavy fault occurs, causing both the feeder and machine breakers to open, after the faulty feeder has been locked out of commission, the machine is still available to supply power to other sound feeders.

Load Measuring Scheme. In this scheme a high resistance is connected across the terminals of the breaker so that when the breaker opens on fault the resistance is inserted in series with the load and allows a small current of from 2 to 5 per cent of normal full load of the feeder to flow, to enable the resistance of the load circuit to be measured by taking the voltage drop either across the load circuit, or across the limiting resistance.

While this scheme works well in feeders connected to an isolated system (one that is not fed from any other point), it can easily be shown that, if used on feeders connected to a system fed from other points, the breaker will reclose automatically on to a fault under certain conditions.

This scheme is not suitable for railway systems where train auxiliaries have a low standstill resistance which would prevent the breaker reclosing, although in actual fact it would be perfectly safe for it to do so.

The disadvantage of this scheme is that the feeder is always alive through the resistance, and so when working on a faulty feeder it is necessary to earth the feeder between the fault and the breaker, while the work is being done, otherwise immediately the fault is removed the feeder is at full potential.

The temporary earth should not be removed until all repairs are done.

Load Limiting Resistance Scheme. Some manufacturers favour the scheme of inserting a resistance in series with the feeder, when an overload occurs, to limit the current. These resistances to be of any use must have a fairly long time constant, and are, therefore, expensive and bulky.

If they have only a short time constant, then, unless the overload is of very short duration, they will become overheated and the thermostat protecting them will

operate and disconnect the feeder, which will then be out of commission for some time while the limiting resistance is cooling down to a temperature at which it is again safe to reconnect it in circuit.

The real need for load limiting resistances, except in very special circumstances, has yet to be proved.

Intermittent Feeling-out Scheme. This scheme is so called because when the feeder breaker opens on fault a by-pass circuit is made at definite time intervals to measure the load on the feeder.

With this scheme a high-speed circuit breaker is usually employed to protect against overloads or short circuits.

Following the opening of the high-speed circuit breaker due to a fault, a contactor closes after a time interval and completes the circuit through a limiting resistance which allows 20 to 30 per cent of full load current to pass. In series with the resistance and contactor is connected a current transformer, across the secondary of which is connected a relay.

If the fault still exists when the contactor closes, the rate of rise of current in the by-pass circuit will be such as to induce a high potential in the secondary of the current transformer which operates the relay and opens the contactor. The contactor recloses after a time interval and this operation repeats itself until the fault has cleared.

The removal of the fault enables the contactor to remain closed for a short time and the feeder breaker recloses.

For the safety of the repair gang, with this scheme, it is necessary before they start work on clearing a fault to thoroughly earth the system between the fault and the feeder breaker. After the repairs have been made this earth should be removed. If the repair is likely to take a long time it is advisable to visit the

sub-station and entirely isolate the feeder, otherwise the duty on the feeling-out contactor is very severe.

This scheme is very suitable for railway systems, as the current allowed to flow round the by-pass circuit is sufficient to supply the auxiliary motors, etc., to get away from rest.

HIGH-SPEED CIRCUIT BREAKERS

The need for the high-speed circuit breaker has been dealt with in a previous paragraph, and as this is such a very important feature in connection with the protection of machines and also the system, it is proposed to go fully into this.

There are several types of high-speed circuit breakers on the market, and the construction and operation of one of these, illustrated in Fig. 4, will now be described.

Construction. The breaker comprises the holding-magnet system (complete with holding coil) and a moving armature heavily spring-biased to the open position. The armature can be moved to the closed position by means of a special closing coil, or, alternatively, by hand operation, and then retained in the closed position by the pull due to the holding coil. The holding-magnet has a " bucking " bar assembled on its pole face and the connections are such that the magnetic flux due to the main current, or a portion thereof, passing through the " bucking " bar will—on heavy overloads—so deflect the magnetic flux of the holding coil that the heavy springs are able to pull the armature to the open position.

The closing mechanism is arranged on the trip-free principle, that is to say, when the breaker is closing the main contacts are not allowed to touch until the operating parts, which brought the magnet armature into contact with the holding coil magnet, have returned to the " open " position as effected by the de-energizing

of the closing coil (or the return of the manually-operated link to the " off " position). Thus, the breaker is free to open immediately, if when the contacts close a heavy overload or short-circuit exists.

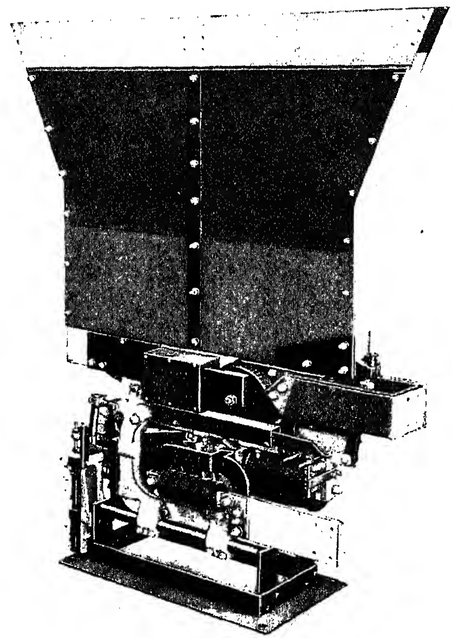


FIG. 4. HIGH-SPEED CIRCUIT BREAKER, 3000 VOLTS, 1600 AMP.

The circuit breaker is equipped with an inductive shunt connected in parallel with the " bucking " bar, which shunt carries a portion of the main current. Under steady load conditions the distribution of the current between this shunt and the " bucking " bar is determined by the resistance of the two parallel circuits. With a rapidly rising current, however, such as occurs during short circuit, the division of current is determined by the inductance as well as the resistance of the two paths. Iron washers are assembled on the shunt to provide the necessary fixed inductance.

The arc chute construction is such that the contacts of the breaker are between the poles of the blowout magnet and directly underneath the arc chute. The

blowout magnet is excited by series blowout coils designed to give an intense field of small area around the main contacts. When the contacts begin to part the flux set up by the blowout magnet forces the arc up into the long narrow slots in the chute, where the arc quickly cools and collapses, thus opening the circuit. The arcing spaces are materially narrower than the contact tips, thus increasing the resistance of the arc-stream for a given length and giving the maximum cooling effect to the vapours. The arc-chute is hinged at one end so that it may be swung back to facilitate inspection of the contact tips.

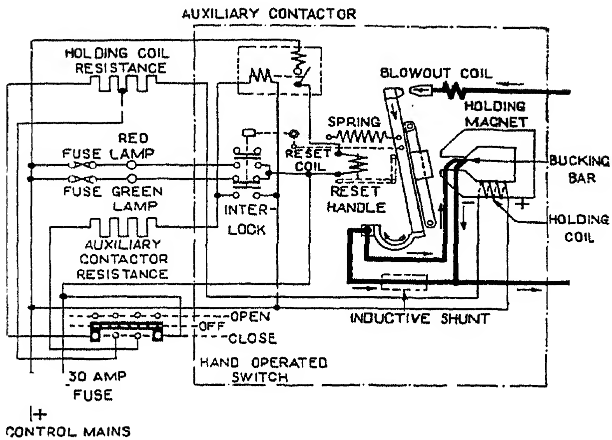
The 1500 and 3000 volt circuit breakers are provided with an additional blowout coil in the arc chute, which is automatically cut into the circuit during the time the arc is being ruptured. This auxiliary blowout divides the arc into two parts and further assists in making an effective blowout.

Operation—Closing. The control circuits for closing the breaker electrically are illustrated in Fig. 5.

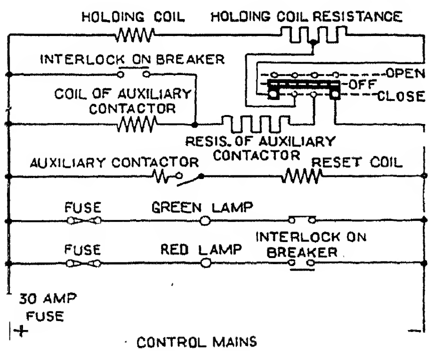
The connections are such that normally, in the " off " position of the control switch, the holding coil circuit is completed, which circuit is still maintained when the switch is thrown to the " close " position. It will be seen that when the switch is thrown to the " close " position, firstly, a portion of the resistance in series with the holding coil is short-circuited, thus causing the holding coil to be over-excited, to assist the closing of the breaker and to ensure consistency of calibration; and, secondly, the operating coil circuit of the reset contactor is completed and the contactor closes, which, in turn, energizes the closing coil of the breaker.

The pull due to the closing coil then operates the reset lever, and thereby mechanically closes the breaker.

At this stage the main contacts of the breaker are



Complete connections



Control circuits only

FIG. 5. CONNECTIONS OF HIGH-SPEED CONTACTOR CIRCUIT BREAKER, WITH SEPARATELY CONNECTED HOLDING COIL

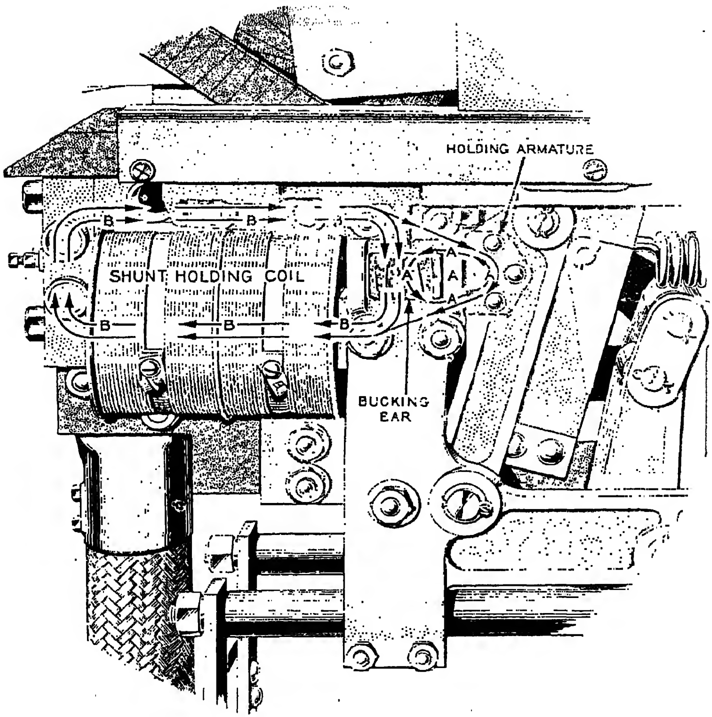
still held apart, so as to obtain the trip-free feature described later.

When the breaker closes, an interlock thereon short-circuits the reset contactor coil, thus de-energizing this contactor which, in opening, disconnects the closing coil from the supply, and allows the closing lever to return to the "off" position. The return of the closing lever to the "off" position permits the main contact of the breaker to close, thus completing the main circuit. When the control switch is released it returns to the "off" position, interrupting the coil circuit of the reset contactor and re-inserting the resistance in series with the holding coil, thus reducing the flux in the holding magnet system to normal.

Non-automatic Opening. To open the breaker non-automatically, the control switch is turned to the "open" position, thus de-energizing the holding coil circuit, which allows the holding magnet to release the armature, and the breaker opens.

Automatic Opening. When the circuit breaker is closed the blowout coils, main contacts and "bucking" bar are in series with the circuit protected, the breaker is held in the closed position by the small laminated armature on the moving contact arm which bridges the gap in the holding magnet. The "bucking" bar is located in the gap between the poles of the holding magnet and in close proximity to the armature. The current flowing through the "bucking" bar therefore produces a maximum change in the armature flux without appreciably affecting the flux in the holding magnet. On the occurrence of a short circuit the differential flux set up by the current in the "bucking" bar deflects the flux produced by the holding coil from the armature to the iron located in the loop of the "bucking" bar in the gap of the holding magnet. Thus, the moment the flux flowing through the

armature is reduced to a predetermined value, the armature is released and the powerful springs return the main contacts to the open position with an extremely rapid action.



(*B.T-H.*)

FIG. 6. SKETCH SHOWING MAGNETIC CIRCUITS OF HOLDING COIL AND "BUCKING" BAR

NOTE.—Outer circle arrows show normal path of flux which keeps holding armature in the closed position.
The arrows marked "A" indicate flux due to current flowing in the "bucking" bar.
The inner circle arrows marked "B" show path of holding coil flux during short-circuit conditions. It will be noticed that this flux does not pass through holding armature.

The magnetic circuits and principle of operation are illustrated in Fig. 6.

It will be seen from Fig. 6 that the breaker only trips when the current passes in one direction. If the current reverses, the flux produced by the " bucking " bar assists the flux produced by the holding coil to hold the breaker closed.

This polarized feature is extremely useful for selective operation, described elsewhere.

Inductive Shunt. The circuit breaker is sometimes equipped with an inductive shunt around the " bucking " bar, which carries a portion of the main current. Under steady load conditions the distribution of the current between the shunt and the " bucking " bar is determined by the resistance of the two parallel circuits. With rapidly rising currents, however, such as occur during short circuits, the division of current is determined by the inductance as well as the resistance. Iron washers are assembled on the " bucking " bar shunt to provide the necessary fixed inductance.

The inductance of the shunt is adjusted to give a lower tipping point for rapidly rising currents than for steady currents. Thus, when a short circuit occurs, the current rises at a very rapid rate, and the breaker opens at a lower value than would be the case with a steady load. The proportion of resistance to inductance in the two circuits is such that resistance predominates for ordinary overload, but in case of short circuits inductance predominates, resulting in a lowering of the trip point.

The breaker will completely disconnect the fault in ·008 to ·015 sec. if there is no reactance in the circuit other than that of the machine it is protecting.

Fig. 7 shows the oscillograph records of short circuit tests on a 1200 kW 600 volt rotary convertor.

Curve 1 shows the time taken to clear a dead

short circuit by a standard switchboard type of circuit breaker. It will be noticed that the current has reached a maximum value some time before the breaker starts to reduce it.

Curve 2 shows the time taken to clear the same fault

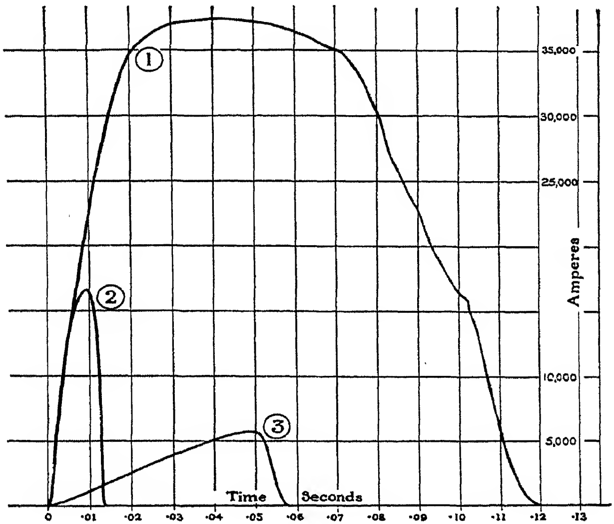


FIG. 7. B.T-H. OSCILLOGRAPH RECORDS OF SHORT CIRCUIT TESTS ON 1200 KW 600 VOLT ROTARY CONVERTOR IN TRACTION SERVICE

1. Standard circuit breaker on dead short-circuit.
   Time to clear fault . . . . 0·12 sec.
2. High-speed circuit breaker on dead short-circuit.
   Time to clear fault . . . . 0·013 sec.
3. High-speed circuit breaker on distant short-circuit.
   Time to clear fault, with two miles of conductor rail between fault and breaker . . . . . . 0·057 sec.

by a high-speed circuit breaker. In this case the current is reduced before reaching half its maximum value and the fault is cleared in approximately one-tenth of the time.

Curve 3 shows the time taken to clear a fault with

two miles of conductor rail between the fault and the high-speed circuit breaker. It will be noticed here how the inductance of the rails keeps down the rate of rise of the current.

During the above test the circuit breakers were set to trip at approximately 5000 amp.

Calibration. There are two chief methods of changing the value of the current which will trip the breaker—

(*a*) By changing the reluctance of the holding coil magnetic circuit.

(*b*) By changing the resistance of the inductive shunt in parallel with the " bucking " bar.

(*a*) *By changing the reluctance of the holding coil magnetic circuit.*

The resistance of the " bucking " bar and inductive shunt being fixed, the value of the current in the " bucking " bar for any steady current is a definite percentage of the total current flowing.

The current required in the " bucking " bar to release the breaker armature is determined by the magnetic flux holding the armature closed. Any change of calibration is effected by keeping constant the ampere turns of the holding coil and varying the flux or holding power of the armature by changing the reluctance of the holding coil magnetic circuit. For this purpose two calibrating screws are inserted in the magnetic circuit near the end of the holding coil. By turning both of these screws out of the steel bar the reluctance of the holding magnetic circuit is increased, thus decreasing the magnetic flux holding the armature closed and allowing a lower main current in the " bucking " bar to trip the breaker. The breaker is calibrated by marking the " trip current " for a number of different positions of these calibrating screws on the adjacent brass plate.

The disadvantage of this method is that when the

breaker is set to trip at the minimum setting, a small variation of the voltage across the holding coil has a large effect on the trip point, as the flux density is a long way down the saturation curve.

This method of calibration should, therefore, only be used where the voltage across the holding coil is approximately constant.

To partially overcome this defect the second method of changing the calibration is used.

(*b*) *By changing the resistance of the inductive shunt in parallel with the " bucking " bar.*

To prevent the variation of the voltage across the holding coil affecting the calibration to a great extent, it is necessary to keep the iron circuit as nearly saturated as possible. This at once prevents changing the calibration by the first method described. By passing a smaller or larger proportion of the main current through the " bucking " bar (with constant current in the holding coil), the value of current required to trip the breaker may be increased or decreased respectively. For this purpose the inductive shunt is made, so that by means of a slider the resistance of the shunt is changed.

Increasing the resistance of the shunt decreases the value of current required to trip the breaker, and vice versa.

In this case the breaker is calibrated by marking the trip current on the variable shunt for a number of different positions of the slider.

CROSS-TIES AND TRACK SECTIONALIZING

Until comparatively recent years the system of using cross-ties and automatic track sectionalizing in railway electrification schemes was little, if ever, used.

This was probably due to the fact that automatic switchgear had not then reached the high standard of

perfection which it has to-day. It is felt that even to-day many engineers have not considered the problem on their systems to the extent that they might have done, nor do they realize the advantages to be gained by adopting this system.

Let the advantages of using cross-ties now be considered—

By tying the overhead trolley wires, or the running rails, as the case may be, of the various tracks running parallel with each other, together, an immediate saving in power results by the reduction of the copper loss, and a more uniform voltage over the entire system. The increased voltage means higher speeds and greater efficiency.

The curves on Fig. 8 show the voltage drop on a 1500 volt four-track system, as a load of 1000 amp. moves from one sub-station to the next, which is located 20 miles away, under various conditions of cross-ties. The total resistance per mile of trolley and return has been assumed at ·04 ohms.

Curve 1 shows the voltage drop if only one track is used (i.e. no cross-ties).

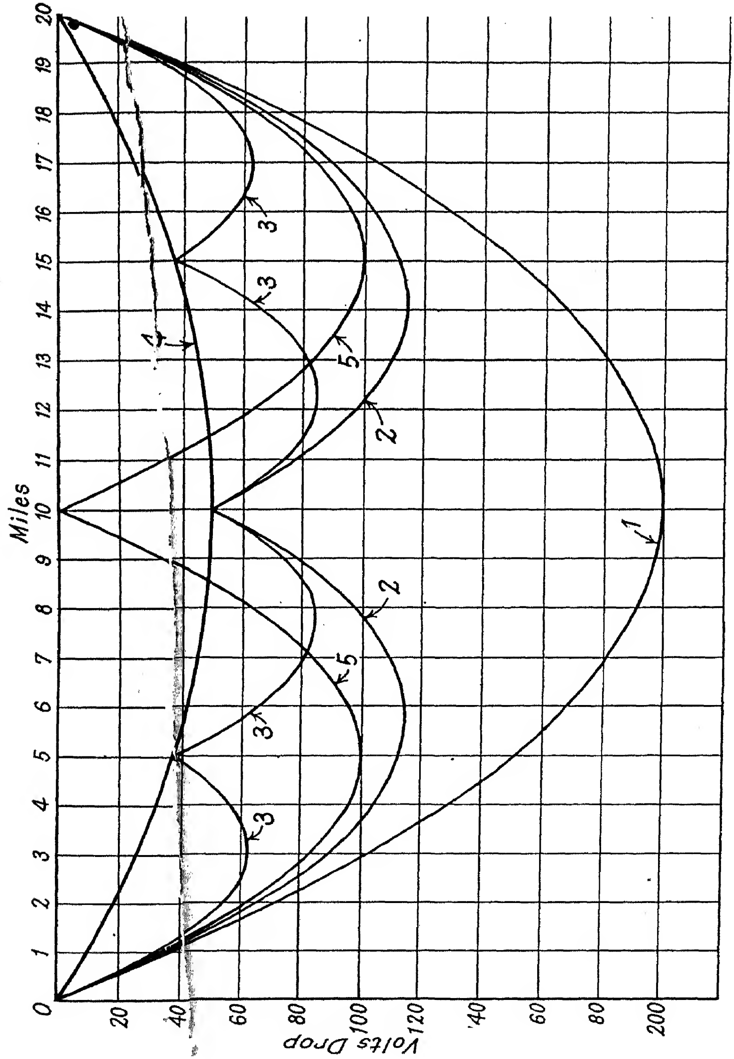
Curve 2 shows the voltage drop if the four tracks are tied midway between sub-stations.

Curve 3 shows the voltage drop if the four tracks are tied at three equidistant points.

Curve 4 shows the imaginary conditions of a four-track road cross-tied at an infinite number of points.

Curve 5 shows the voltage drop if an intermediate sub-station is installed and no cross-ties are made.

The areas of these curves represent the copper losses under the various conditions, and the advantage gained can easily be seen. Comparing Curve 2 and Curve 5 it will be seen that the cross-tie is nearly as effective for the particular load condition as installing an intermediate sub-station.


Miles
0
1
2
3
4
5
6
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9
10
11
12
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15
16
17
18
19
20
Volts Drop
20
40
60
80
100
120
'40
60
80
200
1
2
3
4
5

Once it has been decided to tie the tracks together it becomes necessary to install apparatus which will sectionalize the tracks from each other if a fault develops on one, so that it does not put all the tracks out of commission.

Of necessity, any apparatus installed to sectionalize the tracks on the occurrence of a fault must either be remote controlled, which adds considerably to the expense, or fitted with reclosing devices. Sending along an operator to reclose the breaker after every opening is out of the question.

The best form of breaker to use for this purpose is a high-speed circuit breaker, similar to the one described, for the following reasons—

It is robust, and therefore can operate a large number of times without any attention.

It is very rapid in operation and therefore disconnects the supply from the fault before any great damage is done, and in this way keeps down the cost of maintaining the system.

It is selective, due to its inherent polarized characteristic.

The automatic reclosing features are simple, and due to its being held in electrically, it can be opened without the aid of pilots by making the system dead.

Now consider the various methods of making the cross-ties, and the protection—

Fig. 9 shows a very simple scheme for tying a double track fed from two sub-stations 1 and 2, with high-speed circuit breakers connected in such a way as to utilize their polarized characteristics.

Here the cross-tie is made by breakers *A* and *B*, their control circuit being fed from the trolley lines at points *a* and *b* respectively. The sub-station feeder circuit breakers are shown at *C D E* and *F* respectively, and these are preferably of the high-speed type.

It may be asked, Why install two polarized breakers when apparently one breaker which will operate due to current in either direction will do? The first reason is that it must be of the high-speed type if the feeder breakers are high-speed, otherwise it would not trip; and, secondly, if two polarized breakers are not used extra apparatus would have to be used to determine when it was again safe to close the single breaker, as the control of the breaker would have to be taken from a predetermined trolley, but the breaker would have to be prevented from reclosing if a fault had developed in the other trolley. When this is all taken into account, it will be found that it is very little more expensive to install the two breakers.

In the case of a fault occurring at *X*, the fault will be fed directly from the machines in sub-stations 1 and 2, through the feeder breakers *D* and *E* respectively, and indirectly through feeder breakers *C* and *F* in the sub-stations, and through the sectionalizing breakers *B* and *A*. The direction of current flowing to the fault, as shown by the dotted arrows, is such that it is in the wrong direction to cause breaker *B* to trip, but right for breaker *A*. Thus breaker *A* opens, and *B* remains closed. Feeder breakers *D* and *E* also open, thus entirely disconnecting the fault from the supply.

As the control circuit for closing breaker *A* is taken from the trolley which is now dead, it cannot reclose until either feeder breaker *D* or *E* has been reclosed and again made the trolley alive.

This scheme, while giving all the advantages of the cross-tie with regard to more uniform voltage on the system, etc., does not help the traffic controller to get the trains moving. as just as much track is out of commission while the fault is being repaired as would have been the case if no cross-tying had been done.

Fig. 10 shows a scheme using the cross-tie together

with a more complete method of sectionalizing than that used in Fig. 9.

In this scheme the tie bar is connected to the trolley lines through circuit breakers *A B. C* and *D*, their control circuits being fed from the trolley lines at points *a b c* and *d* respectively; the sub-station feeder breakers connected to the sections of the trolley lines under consideration are shown at *E F G* and *H*. In the case of a fault occurring at *X*, this fault will be fed directly from the machines in sub-station No. 1, through feeder breaker *F*, which will thus be caused to open, and indirectly from the machines in sub-station No. 1, through feeder breaker *E* and the machines in sub-station No. 2, through feeder breakers *G* and *H*, through the cross-tie sectionalizing breakers *B D* and *C* respectively, and then through breaker *A*. It will be seen that the direction of the current flowing to the fault, as shown by the dotted arrows, is such that for all the cross-tie sectionalizing breakers, except *A*, it is the reverse of that required for opening, as shown by the full arrows. The current flowing through breaker *A* will cause it to open, however, and thus disconnect the fault from the system on one side, circuit breaker *F* disconnecting it from sub-station No. 1 on the other side.

As the control circuit for the breaker *A* is taken from the section of the trolley line the breaker is protecting, the breaker will not again reclose automatically until the feeder circuit breaker *F* has been closed and the voltage of the section is again normal.

To prevent a train bridging the sectioning point and so making a faulty section alive from a sound section or extending the fault to a sound section, an isolating section is very often used, interposed between the sections.

To get continuity of the supply when both sections

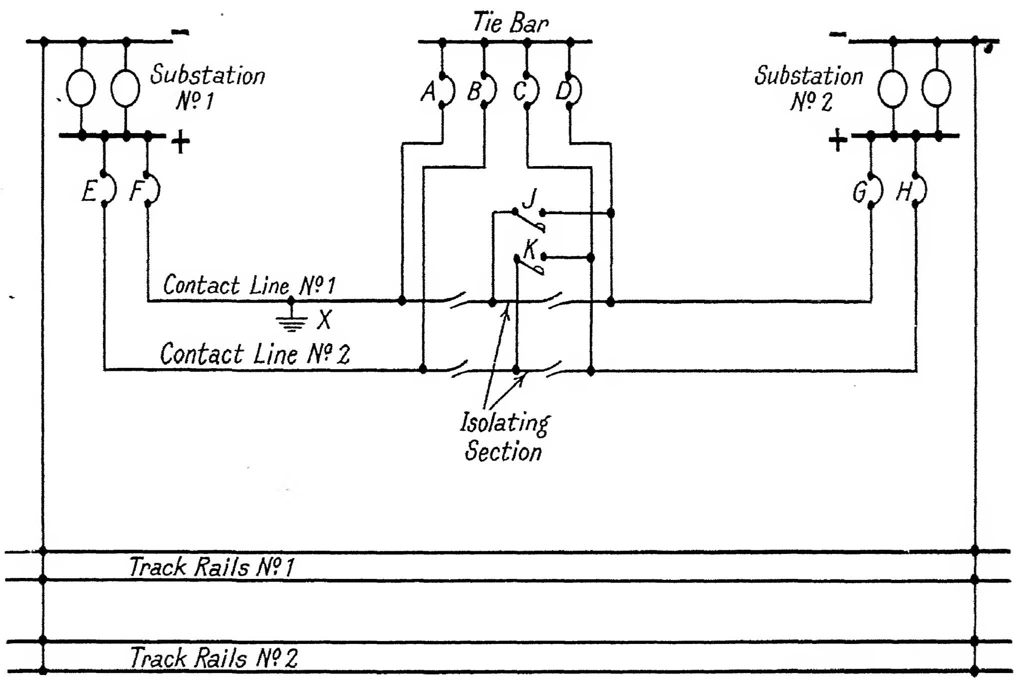

FIG. 11. DIAGRAM OF CROSS-TIE AND SECTIONALIZING WITH ISOLATING SECTION

are alive necessitates making the isolated section alive. On the other hand, this isolated section must always be dead if either of the sections on each side of it is dead.

This can best be accomplished by a plain contactor without any protective features, the operating coil circuit of which is interlocked with the respective track sectionalizing breakers.

A diagram of this arrangement is shown in Fig. 11.

In this diagram the isolating contactor *J* is associated with the track sectionalizing breakers *A* and *D*, and contactor *K* with breakers *B* and *C*, and their coil circuits are interlocked with their respective breakers.

Assuming a fault to occur at the point marked *X*, the feeder breaker *F* in substation No. 1 and track sectionalizing breaker *A* will open, thus disconnecting the faulty section. By means of an auxiliary switch on breaker *A* the circuit of the coil of contactor *J* will be interrupted; thus contactor *J* will open to disconnect the isolating section from the supply. Any train passing from sub-station No. 2 towards sub-station No. 1 along track No. 1 will run off the sound portion of track No. 1 on to the isolating section before it reaches the faulty section and so cannot bridge the sectionalizing point and connect the fault to the sound section.

When the fault has been cleared and feeder breaker *F* reclosed, the sectionalizing breaker *A* will automatically close, immediately followed by contactor *J*, since its coil circuit will again be completed by the auxiliary switch on breaker *A*.

Having gone into the case when only one sectionalizing point is used between adjacent sub-stations, now consider the scheme when there are two sectionalizing points between adjacent sub-stations, as illustrated in Fig. 12.

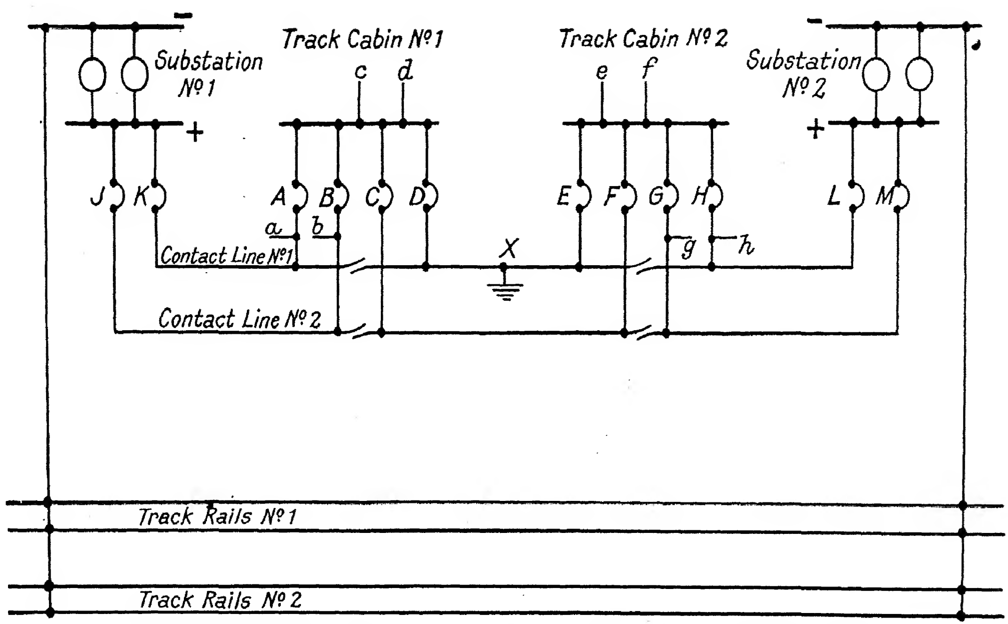

FIG. 12. DIAGRAM OF CROSS-TIE AND SECTIONALIZING AT TWO POINTS BETWEEN ADJACENT SUB-STATIONS

In this case the sectionalizing breakers *A B G* and *H* operate in exactly the same way as previously described, taking their control supply from points *a b g* and *h* respectively. In the case of breakers *C D E* and *F* it is necessary to take the control supply from the tie bar instead of from the section of track they are protecting. The reason for this is obvious if a fault occurs at *X*. This causes breakers *D* and *E* to open, and this section cannot again be made alive until one or other of the breakers has reclosed.

When the control supply is taken from the tie bar it is necessary to install one or other of the reclosing schemes described on page 1534 (Automatic Reclosing Direct Current Feeders) in order to prevent the breakers pumping in and out when a fault persists.

MAINTENANCE

While the maintenance of automatic sub-stations is being dealt with in the previous section, the writer thinks that a few words on this subject will not be out of place here.

It is impossible to lay down a hard and fast rule how often the apparatus should be cleaned and overhauled, as it entirely depends upon the conditions under which the equipment is called upon to operate, and must be determined by experience.

When first installed, a very careful and frequent watch should be kept to see that every device operates satisfactorily, but once the complete equipment has settled down the inspections need not be so frequent. Over-maintenance is as bad as under-maintenance.

The apparatus forming a complete equipment can be divided into four classes—

(*A*) Apparatus which has to make and break the main alternating currents and/or direct current circuits.

(*B*) Control contactors or contactors dealing with relatively small currents.

(*C*) Control relays which are called upon to operate frequently.

(*D*) Protective relays which are only called upon to operate under fault conditions.

The maintenance of the above four classes will be dealt with separately.

(*A*) *Apparatus which has to make and break the main alternating current and/or direct current circuits.*

Main Contacts. If they are of the type which make and break the circuit as well as carrying the current, they should be examined from time to time to see if any large globules of copper are formed which would prevent good contact being obtained, and these should be removed.

It has been found from experience that the very small globules formed on the contacts when the arc is broken are not detrimental, but, in fact, help to obtain a good contact surface as the closing force is sufficient to flatten them out. As the contacts wear and burn away they should be renewed before they have worn to such an extent that they give trouble.

If of the type which never make or break the circuit, they should occasionally be cleaned with a very fine emery or the like to remove any oxide film which may form and cause overheating.

Arcing Contacts. When these are provided, it is important that they are kept in good condition and renewed before they are worn too thin.

The main contacts of apparatus provided with arcing contacts are entirely unsuitable for rupturing an arc, and if the arcing contacts are not kept in good condition the arc may get on to the main contacts with disastrous results.

Contact Pressures. The contact pressures between

the fixed and moving contacts should be checked from time to time, and if found to be low should be corrected, otherwise overheating will occur.

There are two causes of low contact pressure, one being wearing of the contacts, and the other weakening of the springs.

Arc-chute. The arc-chute, together with the blowout coils, is provided to rupture efficiently the arc and to direct it so that it does not do any damage to apparatus near by.

After a number of arcs has been ruptured it will be found that a copper deposit is left on the arc-chute sides, and if this is allowed to accumulate will be the cause of failure to rupture the circuit, thus it is necessary to remove this deposit by scraping.

Auxiliary or Interlocking Contacts. These should be thoroughly cleaned from time to time as required. If there is any excessive burning of the contacts the cause should be investigated and removed. It will probably be one of the following reasons—

(*a*) Partially shorted coil of the device it is controlling.

(*b*) Short-circuited resistance, if any in the circuit.

(*c*) Open circuit in the potentiometer resistance, if this type of connection is used.

(*B*) *Control contactors or contactors dealing with relatively small currents.*

Contacts. The contacts should be cleaned when required, and any globules of copper which prevent good contact being made should be filed off.

As the contacts wear or burn away they should be removed before they are too thin, otherwise the contact pressure will become weak, causing failure to complete the circuit.

Arc-chutes. The maintenance required is the same as for the main contactors.

Contact Pressures. The maintenance required is the same as for the main contactors.

(*C*) *Control relays which are called upon to operate frequently.*

Under this heading the relays used in the sequence of operations, and also the regulating relays used while the unit is running are included.

Great care should be taken to ensure that the contacts are kept clean and that the mechanism is perfectly free.

Pivots and the like should occasionally be examined and cleaned if required, after which they should be wiped with a clean oily rag to prevent rusting.

(*D*) *Protective relays which are only called upon to operate under fault conditions.*

As it is very seldom that these relays operate, it is all the more essential to give them a thorough inspection regularly.

To ensure that the contacts are in good condition and the relays are mechanically free, a very good plan is to make it a routine that every time a visit to the sub-station is made the equipment be shut down by one or more of the protective relays by operating them by hand.

A log should be kept so as to ensure each one is operated in turn.

After any maintenance has been done, the relays should be operated by hand to make sure that the mechanism is free and the contacts are satisfactory.

If the maintenance is of such a nature that the setting of the relay may have been altered, this should be carefully checked.

If the connections of the contacts are of the series type (i.e. connected to break the circuit) contact is ensured if the equipment goes through its complete sequence, but if of the type which make a circuit when

they operate, after cleaning they should be operated by hand, to ensure that no foreign matter has been left on the contacts.

General. Lubricate the bearings of all devices provided with means for doing this.

Do not use any material such as cotton waste, wool, etc., for cleaning the apparatus, as small particles are sure to be left on the apparatus and will cause failure of contact.

Check the air gaps of the magnet systems occasionally and be particularly careful that the gaps between the fixed and moving portions when the device is closed are maintained, otherwise the device will in all probability fail to open when required due to residual magnetism.

Alternating current magnet systems sometimes develop a loud humming noise and this is usually due to bad contact between the fixed and moving portions. It can be corrected by bedding the magnet faces with a file, but care should be taken to check the gaps when this has been done.

After any maintenance has been done, always run the equipment through its sequence before leaving, to ensure that everything is satisfactory.

Replace all covers which have been removed.

It will be found that the settings of certain relays are affected by the cover, so that after the relay has been adjusted with the cover off, a check should be made with the cover in place.

If there is any difference it should be noted, the cover again removed, and the relay adjusted to compensate for this.

The covers are often made of magnetic material to shield the relays from stray fields.

In conclusion the writer wishes to thank the British Thomson-Houston Company for giving their permission to reproduce the photographs and diagrams.

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